RESEARCH REPORT

PERFORMANCE EVALUATION OF RETROFITTED SOLID MASONRY EXTERIOR WALLS

EXTERNAL RESEARCH PROGRAM

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PERFORMANCE EVALUATION OF RETROFITTED SOLID MASONRY EXTERIOR WALLS

Prepared for:

CANADA MORTGAGE AND HOUSING CORPORATION
NATIONAL OFFICE
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FEBRUARY 2005

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MONTRÉAL QUÉBEC BOSTON

RESEARCH AND DEVELOPMENT REPORT

PERFORMANCE EVALUATION OF RETROFITTED SOLID MASONRY EXTERIOR WALLS

Prepared for: **CANADA MORTGAGE AND HOUSING CORPORATION**
NATIONAL OFFICE
700, Montreal Road
Ottawa, Ontario
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PERFORMANCE EVALUATION OF RETROFITTED SOLID MASONRY EXTERIOR WALLS

D. Khudaverdian

ABSTRACT

Many existing buildings in Canada constructed with solid masonry exterior walls are being renovated and converted from their original commercial or industrial use into residential use. In order to increase energy efficiency and occupant comfort, the addition of thermal insulation is desirable. However, adding thermal insulation along the inside face of the wall is also thought to increase the risk of condensation and frost formation within the wall system during the heating season, as well as prolong the drying time of the wall. This combination can adversely affect the integrity and durability of the building envelope.

Consequently, unresolved questions remain regarding how to best improve the insulative properties of existing solid masonry walls without compromising their durability. There currently exists no means or guidelines available to accurately predict the performance of walls retrofitted using different retrofit approaches. However, performing a series of condition assessments on existing retrofitted wall systems offers a unique opportunity in helping to create a knowledge base and develop basic design guidelines for future solid masonry wall retrofit projects.

This paper presents the results of the performance evaluations based upon visual reviews and computer aided modelling of a number of buildings with retrofitted solid masonry walls and is intended as an initial step towards helping practitioners elaborate on different retrofit strategies by providing shared knowledge on the historical performance of previously retrofitted solid masonry walls.

This project was funded by Canada Mortgage and Housing Corporation (CMHC) under the terms of the External Research Program, but the views expressed are the personal views of the author and do not represent the official views of CMHC.

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MONTRÉAL QUÉBEC BOSTON

PERFORMANCE EVALUATION OF RETROFITTED SOLID MASONRY EXTERIOR WALLS

D. Khudaverdian

EXECUTIVE SUMMARY

A preliminary performance review or condition assessment was performed on ten (10) older industrial/commercial buildings originally constructed with non-insulated solid masonry walls which had recently been or was in the process of being converted for new residential occupancy. Nine (9) of the ten (10) cases included projects whereby insulation was added to the inside face of the masonry wall as part of the retrofit strategy chosen. No new insulation was included in the retrofit strategy for one (1) of the projects

The condition assessment included a visual and review and photographic documentation of the exterior solid masonry walls, review of relevant architectural plans or drawings made available, discussions with the project architects or Owners, and the preparation and comparative analysis of results obtained from computer aided modeling of the vertical envelope of all the buildings under presumed hygrothermal conditions.

The comparative results of the computer modeling of both the original and the retrofit wall assemblies of the case studies, appear to suggest that increasing the thermal resistance along the inside face of the existing masonry wall could provoke conditions favorable to increasing the rate of condensation in the wall assembly under identical ambient conditions (temperature and relative humidity) in six (6) of the nine (9) relevant retrofit cases reviewed. Consequently, there is, theoretically, an increased possibility of masonry deterioration related to these six particular cases.

Two (2) of the cases modeled showed that the insulative retrofit reduced the rate of condensation for these particular buildings.

One of the cases which included a retrofit strategy equipped with a dynamic buffer zone system could not be effectively modeled due to the limitations of the modeling software.

At the time of our condition assessment, very little or no visible signs of deterioration were noted In all cases with the exterior solid masonry walls of the buildings. The results of these initial physical evaluations will act as a benchmark when future assessments of these same exterior solid masonry walls will be conducted.

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MONTRÉAL QUÉBEC BOSTON

ÉVALUATION DE LA PERFORMANCE DE MURS EXTÉRIEURS EN MAÇONNERIE MASSIVE SOUMIS À DES TRAVAUX DE RATTRAPAGE

D. Khudaverdian

RÉSUMÉ

On a procédé à une première vérification de la performance ou évaluation de l'état de dix vieux bâtiments industriels ou commerciaux dont les murs d'origine non isolés étaient en maçonnerie massive, mais qui ont dernièrement été transformés ou sont en voie de l'être à des fins résidentielles., Neuf des dix cas portaient sur des ouvrages où de l'isolant thermique a été rapporté sur la paroi intérieure du mur, selon la mesure de rattrapage retenue. Par contre, la mesure de rattrapage visant l'un des projets ne comportait pas d'ajout d'isolant thermique.

L'évaluation de l'état misait sur un examen visuel ainsi que sur des photographies des murs extérieurs en maçonnerie massive, la vérification des plans architecturaux et des devis disponibles, des discussions avec les architectes ou maîtres d'ouvrage, ainsi que la préparation et l'analyse comparative des résultats obtenus de la modélisation informatique de l'enveloppe verticale de tous les bâtiments dans des conditions hygrothermiques présumées.

La comparaison des résultats de la modélisation informatique aussi bien des murs d'origine que des murs soumis à des mesures de rattrapage dans le cadre des études de cas semble indiquer que l'augmentation de la résistance thermique de la paroi intérieure des murs de maçonnerie existants donnerait lieu à des conditions favorables à l'augmentation de la condensation à l'intérieur du mur dans des conditions ambiantes identiques (température et humidité relative) pour six des neuf cas de rattrapage pertinents à l'étude. Par conséquent, il y a, en principe, une possibilité accrue de détérioration de la maçonnerie en rapport avec ces six cas particuliers.

Deux des cas modélisés montrent que la mesure de rattrapage fondée sur l'isolant thermique a réduit le taux de condensation à l'égard des bâtiments particuliers.

L'un des cas qui comportait une mesure de rattrapage ainsi qu'une zone de tampon dynamique ne pouvait pas faire l'objet d'une modélisation efficace en raison des limites du logiciel de modélisation.

Au moment de l'évaluation de l'état, très peu de signes de détérioration sinon aucun n'ont été remarqués dans tous les murs extérieurs en maçonnerie massive. Les résultats de ces première évaluations physiques serviront de repère lorsque seront menées de futures évaluations des mêmes murs extérieurs en maçonnerie massive.

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TABLE OF CONTENTS

Page

Our Reference: RD-0109-A

- Research and Development Report -

PERFORMANCE EVALUATION OF RETROFITTED SOLID MASONRY EXTERIOR WALLS

1 INTRODUCTION

Over the last decade, a trend has developed in urban centers throughout Canada towards converting older industrial and commercial buildings into residential housing. The majority of these structures, originally constructed during the late 19th century or early 20th century, have a vertical envelope consisting primarily of solid masonry. These exterior masonry walls are often load bearing and may consist of several different types of masonry in a single wall section. As a testament to the durability of these structures many of these older buildings have endured well over one hundred years into their service life.

The conversion process from industrial/commercial usage to residential usage requires several important new design considerations relating to the building envelope. Typically older masonry buildings used for commercial/industrial purposes were constructed with little or no added insulation and very little resistance to air and vapour flow through the envelope. As a result there was excessive heat loss and gain, as well as minimal buildup of humidity within the building walls. By contrast, today's modern residential dwellings demand stricter requirements in terms of offering greater occupant comfort and energy savings. The extent of the changes is of course dependent on the composition and the condition of the masonry wall. Promoters of such conversion projects most commonly wish to preserve the unique architectural appearance of the outer masonry walls. Consequently, the vast majority of retrofit measures on the masonry walls are carried out from within the building envelope.

Currently, there is some debate in the building science community about the potential adverse effects that the addition of insulation may have on the durability of older masonry walls. It is known that insulating masonry on the interior surface will significantly alter the temperature gradient across the wall, which is due to the comparatively large difference between the thermal resistances of insulation versus masonry. Due to the current lack of documented long-term studies or field data relating to the effect of insulating solid masonry walls, it is difficult to establish with reasonable certainty whether insulating previously uninsulated masonry walls could lead to premature deterioration. In order to answer some of the questions regarding this issue, the Canada Mortgage and Housing Corporation (CMHC) through its External Research Program has provided the necessary financial contribution for Patenaude-JBK Inc. to conduct a series of preliminary performance evaluations on actual solid masonry wall structures which have undergone insulative retrofit. White this project was funded by Canada Mortgage and Housing Corporation (CMHC) under the terms of the External Research Program, the views expressed are the personal views of the author and do not represent the official views of CMHC.

The objective of the study was to establish a relationship between the initial composition of the wall, the retrofit approach and the condition of the vertical building envelope over an extended period of time. In particular, the report was intended to complete the following tasks:

i) Identify a series of buildings with various types of solid masonry walls that were retrofitted using different approaches;
ii) Classify the buildings according to their building envelope characteristics;
iii) Evaluate the general condition of the masonry;
iv) Tabulate and analyze the collected data;
v) Execute computer simulations on the anticipated performance of the exterior wall systems prior to and following retrofit of the envelope;
vi) Include a photographic record of each case study;
vii) Help to establish basic design guidelines for the retrofit of older solid masonry walls based on the case study results.

The ultimate goal for this study and those that follow is to compile sufficient field data in order to help to determine what effect the addition of insulation has had on the long-term durability of solid masonry walls, and act as a preliminary step towards helping practitioners elaborate on different retrofit strategies by providing shared knowledge on the performance of previously retrofitted solid masonry walls.

1.1 Common Causes of Masonry Deterioration

Masonry deterioration is most often characterized by visible changes in the masonry assembly which present themselves in the form of cracks, spalling bricks, and the de-bonding of bricks and mortar.

Numerous causes could account for masonry deterioration such as improper design (poor accommodation for movement, poor material selection…etc.), loading changes, poor construction practices, deterioration of the embedded structure, a lack of suitable maintenance, thermal stress, and damage due to freeze-thaw cycles.

Masonry deterioration due to freeze-thaw cycles and deterioration of the embedded structure is often related to inadequate control and resistance to a combination of specific moisture content and thermal cycles (or hygrothermal conditions) to which the masonry wall assembly may be subjected to.

Consequently, as a means to prevent the provocation of masonry deterioration due to a change in hygrothermal conditions, additional analysis and special design requirements should be considered when anticipating building retrofit solutions which may involve altering the thermal resistance and/or moisture control of an existing solid masonry wall.

2 CONCERNS RELATED TO INCREASED THERMAL RESISTANCE

In their original state, solid masonry walls with little or no thermal insulation are submitted to an important temperature gradient. While the mixed assembly of mortar joints bricks, and variable air spaces of an actual masonry wall complicates modeling and accurately evaluating the actual thermal resistance of a given masonry wall, comparative results of measuring the thermal resistance between insulated and non-insulated masonry walls can still be achieved through the analysis of idealized models. Presented below are three idealized models of masonry walls which help to illustrate the effects and concerns relating to increasing the thermal resistance of a solid masonry wall.

2.1 Modeling of Non-Insulated Masonry Wall

In the first idealized model, (shown in Figure 1, below), an air-tight, homogeneous, non-insulated masonry wall, the thermal resistance of the assembly is presumed uniform. The exterior ambient temperature is presumed to be minus -23 deg Celsius while the interior ambient temperature is presumed to be 21 deg Celsius, in order to simulate winter design conditions for Montreal. The wall temperature is shown to be distributed linearly from the exterior to the interior surface. This model illustrates that the temperature gradient promotes heat transfer through the wall towards the exterior during the heating season.

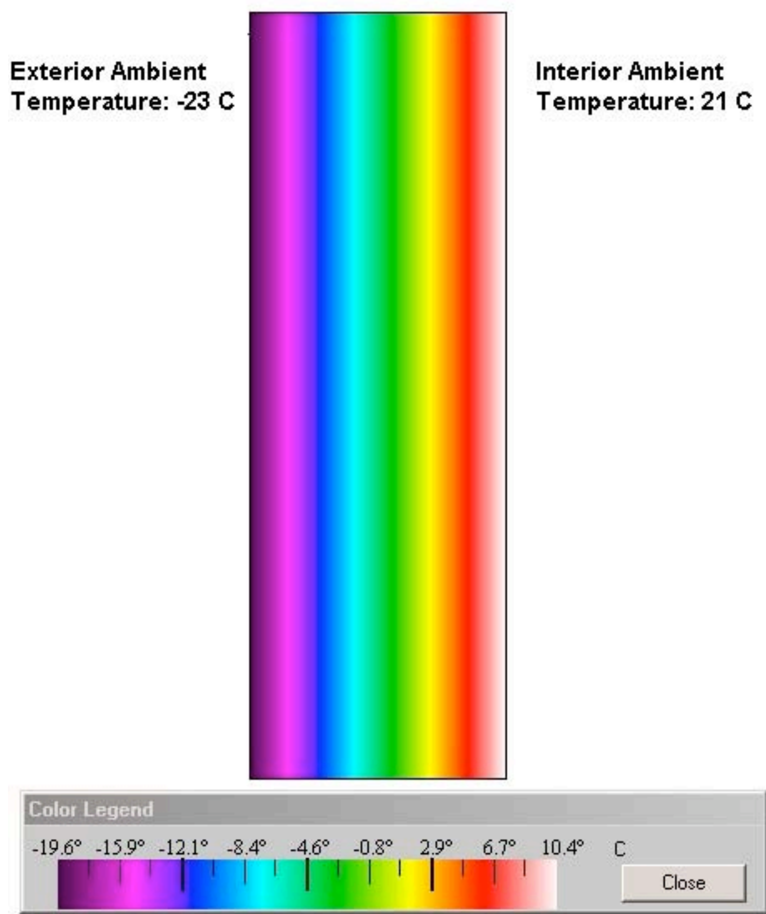


Figure 1. Uninsulated masonry wall

2.2. Modeling of Exterior Insulated Masonry Wall

In the second idealized model, (shown in Figure 2, below) an air-tight masonry wall consisting of three courses of 89mm brick and insulated with 25mm of spray applied polyurethane insulation along its exterior surface is simulated. The thermal resistance of masonry is small compared to that of most forms of insulation. A typical example would be a single course of 89 mm clay bricks, which has a thermal resistance of 0.106 RSI, compared to 25 mm of spray-applied polyurethane, which has a resistance of 1.04 RSI[1]. The large discrepancy between the thermal resistances implies that when put in series, the temperature gradient will be ten times greater in the insulation than in the brick.

Based upon our model shown in Figure 2, and assuming an outdoor ambient temperature of minus –23 °C and an indoor ambient temperature of 21 °C, the temperature of the brick will vary between 8 °C and 17 °C (refer to Example #1 in Appendix A). Thus, if insulation is installed on the exterior face of the wall as shown in this model, the masonry would be subjected to only a minor variation of the indoor ambient temperature (refer to Figure 2). As a result, any trapped moisture within the brick will never reach the freezing point. Consequently the potential for masonry or mortar joint failure due to the freeze/thaw process has effectively been eliminated.

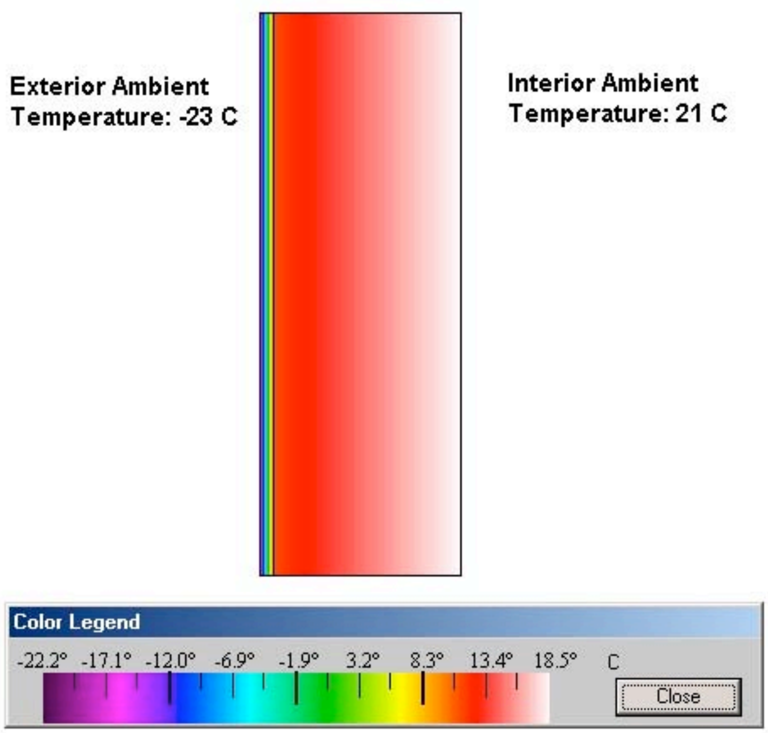


Figure 2. Masonry wall insulated on exterior surface

[1] Assuming a thermal conductivity of 0.84 W/m°C for brick and 0.024 W/m°C for polyurethane.

2.3 Modeling of Interior Insulated Masonry Wall

In order to preserve the aesthetic features of the aged masonry walls, builders will generally opt to insulate from the interior. In the third idealized model shown in Figure 3 below, the same composition of masonry and insulation are again placed in series, but now the insulation has been placed along the inside face of the solid masonry wall. Under the same design ambient temperatures, used in the two previous models, the temperature within the masonry will based upon our simulation would vary between minus –22 °C to minus –12 °C (refer to Example 2 in Appendix A) if the insulation is installed on the interior face of the masonry wall. This simulation helps to illustrate that during the heating season, the insulation placed along the inside face of the solid masonry wall acts as a thermal barrier between the heated interior of the building and the exposed exterior masonry. The interior insulated wall is therefore subjected to the colder average temperatures through more of its assembly in comparison to non-insulated or exterior insulated masonry walls.

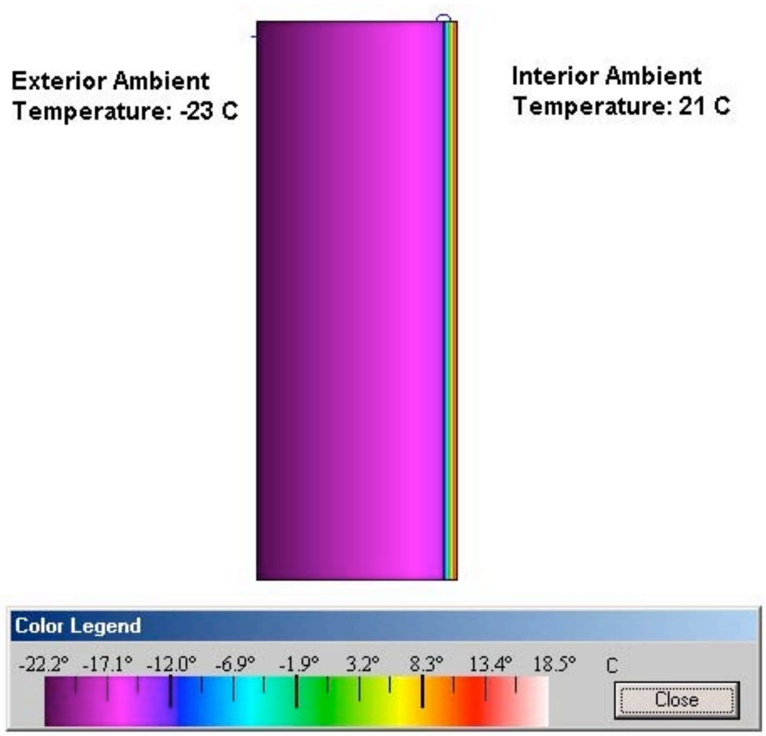


Figure 3. Masonry wall insulated on interior surface

While the three models above present the differences and thermal effects between non-insulated, exterior insulated, and interior insulated masonry walls, it is important to understand that subjecting the masonry wall to overall cooler temperatures alone is not necessarily detrimental to the longevity of the wall. In fact, the materials properties of “dry” mortar and masonry offer excellent resistance against deterioration in below freezing temperatures.

The problems of freeze-thaw induced deterioration generally occur, however, when sufficient moisture becomes entrapped and freezes within solid masonry walls during the heating season regardless of whether the walls have been insulated or not. Moisture is generally introduced within the wall system either through precipitation, or through condensation. When converting industrial or commercial buildings to residential applications, the new residential vocation will often maintain higher indoor relative humidity levels and different air pressure regimes than those maintained in the past. Consequently, in the absence of a suitable vapour barrier and a continuous air-barrier system (not a recommended practice), the risk of moisture accumulation and entrapment due to humid air travel and condensation within the newly retrofitted wall system is increased. The accumulation and entrapment of moisture within the retrofit wall is further promoted by the presence of the added insulation which both increases the cooling rate and reduces the drying rate of the mortar and masonry elements of the wall system. Moisture absorbed by the wall insulation reduces the RSI-value of the insulation and consequently reduces the overall RSI-value of the masonry wall system, which favors frost and ice within the wall system and consequently promotes conditions favorable for masonry deterioration. To summarize, the combination of colder masonry mean temperatures, longer drying time, increased interior relative humidity levels and different air pressure regimes that are generally associated with the interior insulation retrofit of solid masonry walls may adversely affect the integrity and durability of the building envelope if measures are not taken to protect the wall assembly from both interior and exterior moisture sources.

3 GENERAL GUIDELINE FOR INSULATING SOLID MASONRY WALLS

Because of the potential risks with regards to the durability of the masonry, the question of whether the addition of insulation will significantly improve energy efficiency and occupant comfort needs to be addressed. For example, in the case of façades with a high window area over wall area ratio, increasing the thermal resistance of the wall may not provide an impact important enough to justify the addition of insulation on the opaque wall areas unless it is deemed necessary to prevent thermal bridging and condensation associated with thermal bridging. It should be taken into account that air leakage is a significant source of heat loss and also one of the main sources of complaints of occupant discomfort. In the case of older buildings, because of their advanced age and construction, significant air leakage across the walls is to be expected.

An emphasis should therefore be directed towards including both a continuous and effective air- and vapour-barrier systems and in ensuring that potential thermal bridging and associated condensation in these areas are identified and addressed.

3.1 Controlling Humidity Sources

It was previously stated that masonry can withstand temperatures below freezing without negative repercussions to the durability of the wall, particularly in the absence of moisture. In fact, most non-insulated masonry buildings in service today regularly see the temperature of the masonry wall system fall below freezing without any signs of deterioration. To minimize the risks related to increasing moisture accumulation within the wall system when adding insulation to the inside face of the exterior solid masonry wall, the following preliminary guidelines are suggested towards helping to control exterior and interior humidity sources:

I) Minimize rain penetration into the wall assembly:

Rain penetration is a potential large source of water ingress within a wall assembly and is often reflective of the quality and condition of the masonry units and mortar joints. The addition of insulation must be combined with a detailed inspection and repairs of the exterior face of the masonry and mortar joints in order to minimize water intrusion. Other aspects of the building envelope should also be designed to reduce water infiltration and improve water shedding capabilities to direct water away from the wall surfaces, such as the incorporation of suitable window and wall flashings, drip edges, gutter systems, and parapets in order to ensure that the building envelope performs as a continuous rain screen.

II) **Minimize penetration of indoor humidity into the wall assembly through water vapour diffusion:**

In order to prevent humidity transfer through diffusion, it is necessary to include a continuous vapour barrier within the wall assembly. The vapour drive, location, and rate of condensation within a wall assembly depend on several factors. These factors include the type of wall materials used, their order of assembly, the quality of their installation and the temperature and relative humidity conditions maintained inside the building during the heating season.

III) **Minimize penetration of rain water and indoor humidity into the wall assembly through air infiltration and exfiltration:**

The wall assembly must include a continuous air barrier system throughout the building envelope. A well-constructed air-barrier will minimize humidity transfer into the wall system caused by exfiltration of indoor air. The air barrier also contributes in minimizing the air pressure differential across the masonry wall assembly and consequently reducing rainwater penetration induced by air pressure differentials. Reduced air leakage also increases the level of occupant comfort and energy efficiency.

IV) **Minimize the air pressure differential across the exterior wall assembly via the mechanical systems of the building:**

The air pressure differential across the building envelope is the driving force for exfiltration of warm, moist indoor air through the wall assembly for buildings under positive pressure (higher indoor pressure versus lower outdoor pressures) and for rain penetration for buildings under negative pressure (lower indoor pressure versus higher outdoor pressure). The pressure differential across the exterior walls of a building is influenced by stack effect, wind loads and the operation of the mechanical systems. Mechanical systems should be balanced so that a relatively neutral air pressure exists across the building envelope.

V) Control Indoor Relative Humidity

As a means to limit or control the amount of condensation within the wall assembly, the level of indoor relative humidity should be kept to a minimum during the heating season also through mechanical means by incorporating air-exchange systems which dehumidify the heated air and supply and operation of suitable exhausts in areas of high humidity such as kitchens, bathrooms, and laundry rooms. Maintaining a level of between 20% - 30% interior relative humidity for most modern residential construction in Montreal during the heating season is also recommended in order to maintain a reasonable balance between occupant comfort and to limit the degree and potential effects of condensation.

3.2 Increasing Thermal Resistance

When considering occupant comfort and energy efficiency, it is often deemed necessary to increase the thermal resistance of the existing exterior walls. However, increasing the thermal resistance along the interior surface of solid masonry walls will lower the mean temperature of the masonry and significantly increase the drying time of the wall assembly[2] and the cross section of the wall exposed to freezing temperatures. If the guidelines for moisture control are not followed, the combination of colder masonry and increased drying time may result in an increased risk of moisture accumulation, condensation and frost formation within the solid masonry wall, which can lead to freeze/thaw damage and effectively reduce the durability and lifespan of the masonry wall.

4 CASE STUDY ANALYSIS

Only by committing to long term periodic evaluations of actual buildings whose exterior solid masonry walls have recently undergone insulative retrofits, would we be able to obtain solid practical data towards defining and supporting a proven approach towards insulating solid masonry walls.

[2] A simple calculation from Example 1 in Appendix A will show that removing the polyurethane from the wall assembly will result in a heat loss of about 91.5 W/m^2, roughly three times the insulated heat loss.

In order to determine the potential long term effects of insulating solid masonry walls, ten (10) existing buildings having recently each undergone different types of insulation retrofit strategies were located, identified and included within the case studies for this research as a means to compare results over the long term, of all actual field data collected with the theoretical design guidelines for insulating solid masonry walls.

Given that current retrofit practices for insulating solid masonry walls vary from the application of polyurethane foam to the construction of Dynamic Buffer Zone systems, it can be difficult to relate the results of one building to another. In addition, it is often difficult to gauge the effects that the retrofit has had on the masonry itself. Degradation in the quality of the masonry, as previously mentioned, is not necessarily attributable to the retrofit approach of insulating the masonry walls. The design, construction quality, materials quality, climatic conditions, usage by occupants, and the age of the masonry and the building are just some of the possible variables that can have a negative effect on the durability of the masonry. Regular and timely maintenance and repairs can also increase the lifespan of the masonry. Another consideration which adds to the difficulty in assessing retrofit methods, is that one retrofit approach may result in few or insignificant problems for one type of masonry or construction, yet may cause severe degradation over time in another. Consequently, particular care was taken in the assumptions made regarding the comparison of similar case studies used in this report.

The buildings for the case studies used in the report were selected from references obtained from insulation contractors and manufacturers, architects, and through collaborative efforts with government research organizations. Buildings for the case study were chosen so as to represent more recent solid masonry wall retrofit projects of varying insulative techniques. The results of our condition survey of the masonry walls are intended to provide initial benchmarks on the actual condition of the masonry walls for each of the buildings included within the case studies. Subsequent visits and assessments of the masonry walls of each of the buildings are intended to be conducted periodically over the next decade as a means of comparing the future performance of the insulated solid masonry walls of all the buildings, relative to their initial condition. In order to fully understand each building selected for the case studies, it was necessary to accumulate as much information as possible regarding the history of the structure and the composition of the building envelope. The data requisition process included interviews with the building owners, managers, or architect, site visits and visual non-destructive reviews of each of the exterior building walls, and computer simulations of each of the wall assemblies.

4.1 Interviews

Interviews were conducted with building owners, architects, maintenance personnel and/or any individual knowledgeable about the building in question. The majority of the information about the history of each building was obtained through interviews and through the review of any available and relevant plans of the building envelope. For the majority of the case studies, it was necessary to first meet with the individual responsible for the building site in order to gain authorization and access to conduct our site visit.

4.2 Site visits

The key information regarding the current condition of the solid masonry walls included within our research was obtained via site visits and a visual non-destructive review of the vertical building envelope. The site visits were conducted in early 2003. Viewing the buildings first hand was essential to providing an up to date assessment of the masonry. In all cases, a street-level visual review of all façades of the building was performed during the site visits. Any signs of joint failure, cracks, efflorescence, spalling or other deficiencies witnessed in the masonry were noted and photographed. If the building elevation drawings were made available, the locations of each photograph were indicated directly on copies of the plans to facilitate future reference and comparisons. Note that certain deficiencies observed during the visual review are not necessarily due to the insulative retrofit, so no conclusions were drawn to that effect.

Interior inspections were also conducted although access was limited in most of the multi-storey residential units due to difficulties in arranging and obtaining access from individual Owners and tenants. A greater number of interior reviews are expected to be conducted during subsequent visits to these sites in any forthcoming evaluations.

4.3 Computer simulations

The computer simulations proved to be a valuable tool for understanding the behaviour of the different masonry wall compositions. While computer models are useful for illustrating idealized cases of the wall compositions, there are several limitations that must be taken into account when viewing the results from the simulations:

I) There are few computer programs that can simulate the effects of air leakage into a wall assembly of an actual building. Air infiltration and exfiltration can have a significant impact on the interior temperatures and moisture movement and accumulation of a wall assembly, which will affect the temperature gradient and the location of the dew point in the wall. As a result, the simulations quite often lead to inaccuracies in trying to predict the actual temperature, moisture movement, and moisture accumulation within an existing masonry wall

II) Computer models generally do not take into account the inconsistent contact between two materials that can occur at an interface, which generally takes the form of a thin layer of air. However, thermal resistance is directly proportional to the width of an element, so because the interface is extremely small the thermal resistance is proportionately small. An example of this is an L=1 mm air gap between two materials across the entire surface of contact (an absolute worst-case scenario, considering there must be a minimum amount of contact). Since still air has a conductivity of k=0.025 W/m-K, the resulting thermal resistance would be (L/k) 0.04 m^2K/W. In reality the interface would be a fraction of a millimeter and would result in a change in overall thermal resistance of approximately 0.1%. For the purposes of this report and the analysis of the simulations, the material interfaces were not considered.

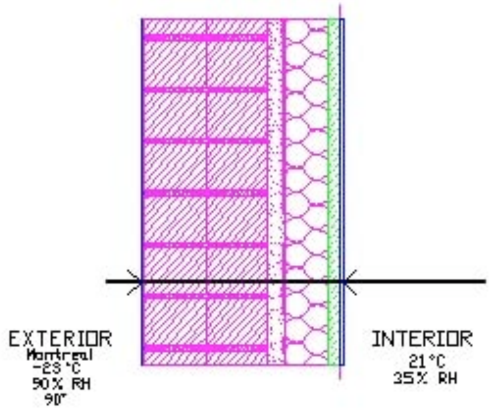
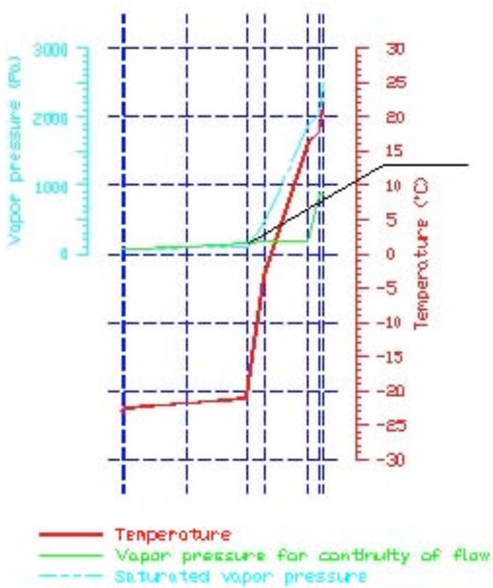
III) Unless additional data through testing is gathered from each of the masonry walls reviewed, it is impossible to determine the exact thermal resistance of each type of masonry for use in the simulations. However, the variation between actual resistance values of masonry and the computer simulation values will always be negligible compared to the significantly greater and well-known values for the thermal resistance of insulation. So while the exact values for individual masonry walls may not be known, the margin for error is sufficiently small to allow for reasonable approximations of wall assembly behaviour.

It is important to note that the hygrothermal simulations were used only to conduct parametric evaluations to determine the change in hygrothermal conditions in the wall before and after the addition of insulation to the solid masonry walls. For the purpose of this report the results from the computer simulations were used solely to illustrate changes in temperature gradients, dew point temperatures, and the rate of condensation between in the original wall assembly versus the retrofit wall assembly. Consequently, due to the limits of the modeling software, the results produced from the computer simulations, such as rate of heat loss and condensation rate of the individual walls should not be considered as accurate representations of the actual hygrothermal conditions predicted in each of the wall assemblies. For comparative purposes, initial modeling was conducted using design parameters for Montreal climate and assuming an exterior ambient temperature of minus -23 deg C., an exterior ambient humidity of 90%RH, interior temperature of 21 deg C., and interior humidity of 35%RH. Additional modeling was also conducted in several cases in order to determine the threshold of interior relative humidity expected to either produce or eliminate condensation within a given wall system. There were two software programs used to simulate the temperature distribution in a given wall assembly, namely *Condense* and *Therm*.

4.3.1 Condense

Condense is an AutoCAD based application that allows the user to input the materials of a wall assembly. The software will then calculate the temperature distribution through each element in the wall based on the thermal resistances of each material. In addition, *Condense* will also calculate vapour pressure and saturated vapour pressure throughout the assembly in order to determine if condensation will occur. The following table describes the data found in a typical *Condense* output.

Table 1. Condense analysis output

<table>
<tr>
<td>
</td>
<td>The user may enter the various materials found in the wall assembly, and the resulting envelope detail will be shown in the upper left corner of the output drawing. The conditions for the exterior and interior environments are shown on the respective sides of the assembly.</td>
</tr>
<tr>
<td>
<table>
<tr><th>DESCRIPTION</th><th>RSI</th><th>R</th></tr>
<tr><td>Exterior air film</td><td>0.03</td><td>0.2</td></tr>
<tr><td>Clay brick fired red, 89 mm</td><td>0.08</td><td>0.3</td></tr>
<tr><td>Clay brick fired red, 89 mm</td><td>0.08</td><td>0.3</td></tr>
<tr><td>Spray. polyurethane 32kg/m3, 25 mm</td><td>1.25</td><td>7.1</td></tr>
<tr><td>Fibreglas batt, 65 mm</td><td>1.4</td><td>7.9</td></tr>
<tr><td>Gypsum aluminum back, 16 mm</td><td>0.1</td><td>0.6</td></tr>
<tr><td>Paint latex int. white mat, 0 mm</td><td>0</td><td>0</td></tr>
<tr><td>Interior air film</td><td>0.23</td><td>1.3</td></tr>
<tr><td>Total Thermal Resistance</td><td>3.12</td><td>17.7</td></tr>
</table>
</td>
<td>The thermal resistance values are shown for each element in the wall assembly. The amounts are listed in RSI and R-value units.</td>
</tr>
<tr>
<td>
</td>
<td>The chart on the left displays the temperature curve as it progresses from the exterior to the interior environments. The remaining two curves represent the vapour pressure (VP) and the saturated vapour pressure (SVP) throughout the assembly. If the VP exceeds the SVP it indicates condensation will occur at the point where the two curves intersect. This location is denoted by an arrow, and corresponds to the dewpoint in the assembly.</td>
</tr>
</table>

Case #1: Condensation occurs —— There is condensation in the given assembly at this location. The condensation rate is 1.587E-08 g/m2/sec. or 1.380E-04 litres/m2/day. The estimated cost for the materials in this assembly is 159.8 $/m2. The heat loss rate is 14.09 Watt/m2. The dewpoint temperature is -17.8 degrees Celsius. Case #2: No condensation occurs There is no condensation for these conditions. The estimated cost for the materials in this assembly is 1838 $/m2. The heat loss rate is 83.12 Watt/m2.	The result of the analysis is displayed in terms of condensation rate and heat loss. If condensation occurred there will be an arrow indicating the exact location. The condensation rate, estimated cost of materials in the assembly, heat loss rate and the dew point are all calculated and displayed as seen on the left.

4.3.2 Therm

The second program used to simulate the temperature distribution in the masonry wall assemblies is a temperature modeling software called *Therm*. This software is more effective than *Condense* in terms of graphically demonstrating the temperature distribution in a wall assembly as it varies from one material to the next. *Therm* also allows for more precision by permitting entry of supplementary data regarding conditions surrounding the wall assembly, such as indoor and outdoor convection coefficients and boundary conditions of the wall assembly. The material database is extensive and can be completely customized to the user's needs. The end result is a very accurate temperature distribution of the wall assembly. A sample *Therm* output is shown below in Figure 4.

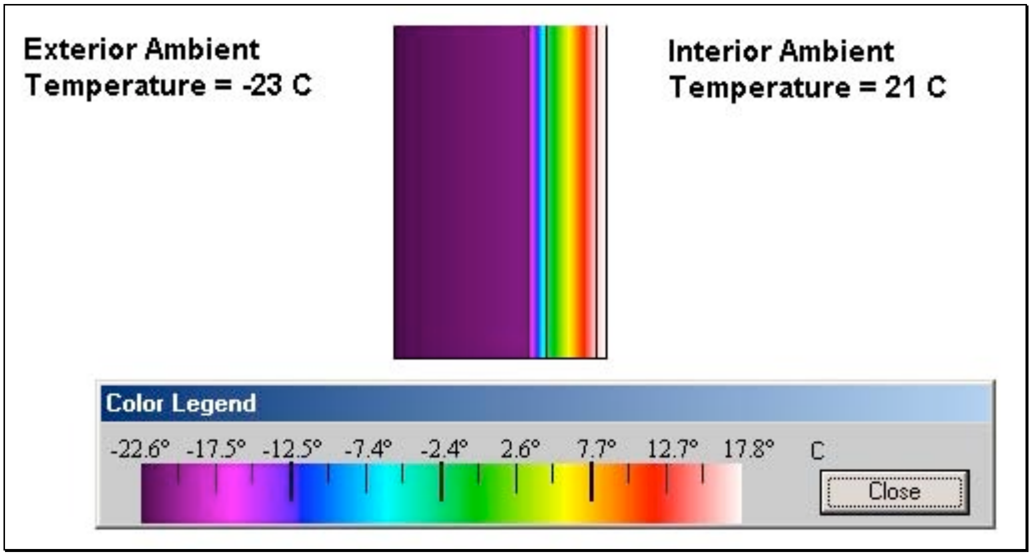


Figure 4. Sample *Therm* output

The output from *Therm* includes a scale drawing of the wall assembly as drawn by the user, and the color legend that describes the corresponding temperatures in the assembly. Note that the author added the exterior and interior temperatures.

5. BUILDING EVALUATIONS

A total of ten (10) buildings which had recently undergone or were in the process of undergoing a major retrofit of their exterior walls masonry were selected to be reviewed and modeled as a means of providing benchmark assessments of the solid masonry walls, and to help determine through comparative physical assessments to be conducted during subsequent visits, the practical long term effect of insulating the inside face of the solid masonry walls using various retrofit techniques.

The exterior cladding of buildings reviewed consisted of multi-wythe masonry brick units, solid stone, limestone blocks, fieldstone, or a combination of various solid masonry elements.

The building evaluations at this preliminary stage were limited to strictly a visual review of the exterior masonry walls. The visual signs of deterioration which were to be tabulated included any signs of significant cracks in the masonry, efflorescence, signs of corrosion, bowing or displaced section of masonry, de-bonded or breakdown of mortar joints, as well as any spalling or missing masonry units.

The intent was to record all masonry deterioration of the retrofit walls observed during this preliminary review and to later compare the condition of the masonry walls with their condition every 3 to 4 years. The degree and scope of continued deterioration would then be compared with the computer modelling in order to try and determine whether a link could be established between the results of the computer modelling and the expected change in the rate of condensation (steady state) between the original wall construction and the new retrofit wall construction.

In eight (8) of the ten (10) case study buildings observed, 1” to 1½” of spray-applied polyurethane insulation were used to insulate the walls. In another case, a combination of polyurethane foam insulation and glass fibre batt insulation was used, while only glass fibre insulation was used in a ninth case which included a DBZ (Dynamic Buffer Zone) system and 1” heated air-space. In one of the case studies, no insulation was added as part of the envelope retrofit for an upscale condominium complex which included stone walls of up to 38” in thickness. This last case study was included as part of the research in order to provide an practical comparison between the rate of deterioration of non-insulated solid masonry walls versus buildings with retrofitted interior insulated masonry walls over the long term.

In all but one of the cases, the buildings reviewed were located in the Montreal area and as such will be subjected to nearly identical climatic conditions. The one remaining building reviewed is located in Léry, Quebec.

The table in Appendix B (Table 1) provides a summary of all the buildings reviewed and general data obtained during our physical assessment of each of the buildings.

The following sections presents the results of our initial condition assessment and the results of the computer models/simulations conducted of both the original and post retrofit wall assemblies. of the ten (10) case studies selected and reviewed in early 2003.

5.1 CASE STUDY #1

Location:

Montréal, Québec

Envelope description

- Solid brick masonry (2+ courses);
- ¾" – 1" polyurethane foam insulation;
- 1 ¾" glass fibre batt insulation;
- ½" gypsum board with aluminum foil backing on 1 ¾" steel furring

Initial construction: 1884

Date of retrofit: 1984

Date of Survey: February 2003

.1 General description

These three 4-storey buildings were built over one hundred years ago. They were originally constructed for industrial purposes and were converted to residential use in 1984. During the retrofit work, polyurethane foam insulation was spray-applied over the interior surface of the solid masonry walls. The assembly was completed with a steel furring frame filled with glass fibre insulation and finished with foil-backed gypsum board sheathing.

.2 Site visit observations

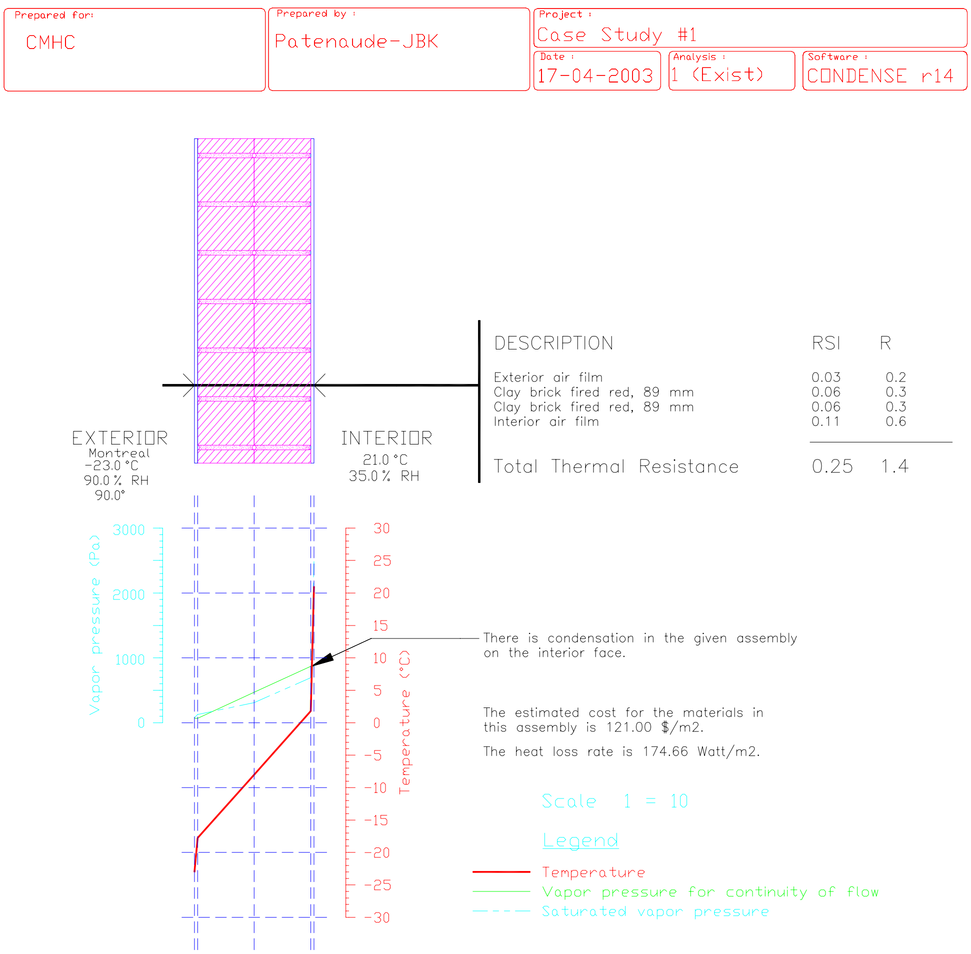
Patenaude-JBK Inc., had previously in an unrelated mandate, performed a condition survey of these buildings, in September 2000. Our assessment of the condition of the exterior masonry walls at that time was that the masonry had not appeared to have been adversely affected in the sixteen years since the retrofit, based upon site observations and discussion with maintenance personnel. Upon returning in February 2003 and comparing photo documentation from the condition survey, there were no visibly apparent changes noted in the condition of the masonry. Some sample photo comparisons from the two visits are provided below. It is clear that the efflorescence stains and faults in the masonry have remained unchanged during the three-year time frame (see attached photos below). No problems to the exterior masonry walls were reported to us during our interview with building personnel.

September 2000	**February 2003**
	
Photograph No. 1	Photograph No. 1A
	
Photograph No. 2	Photograph No. 2A
	
Photograph No. 3	Photograph No. 3A

.3 Modeling Analysis

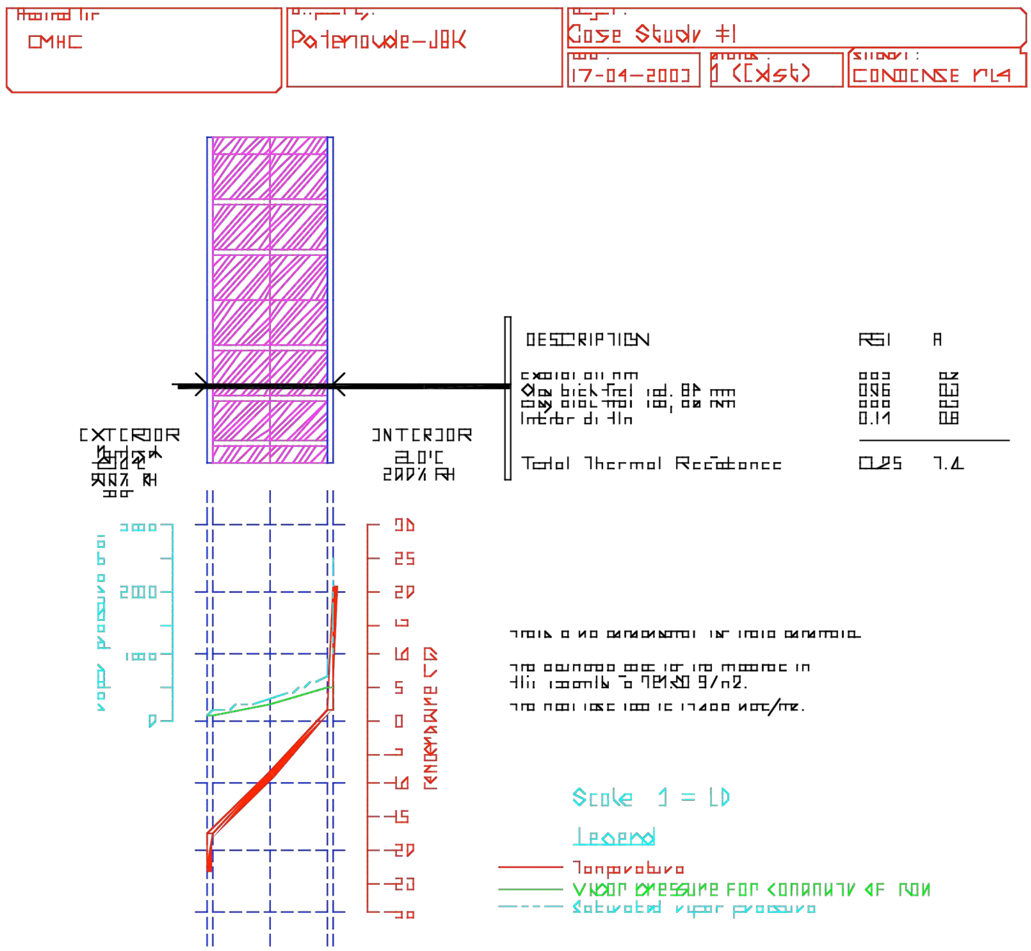
The hygrothermal simulations for Case Study #1, included the idealized modeling and comparative analysis of both the original and retrofit wall assemblies.

Using CONDENSE, the modeling of the original wall composition (see *SIM-1* below) indicated that the total thermal resistance was R1.4 (RSI 0.25) with an average wall temperature of about minus -8 deg Celsius. Under design conditions for Montreal, which include exterior temperature of minus -23 deg Celsius and exterior relative humidity of 90%, and an interior ambient temperature of 21 deg Celsius and interior relative humidity of 35%, the model shows that condensation would be expected to occur along the inside face of the masonry wall.



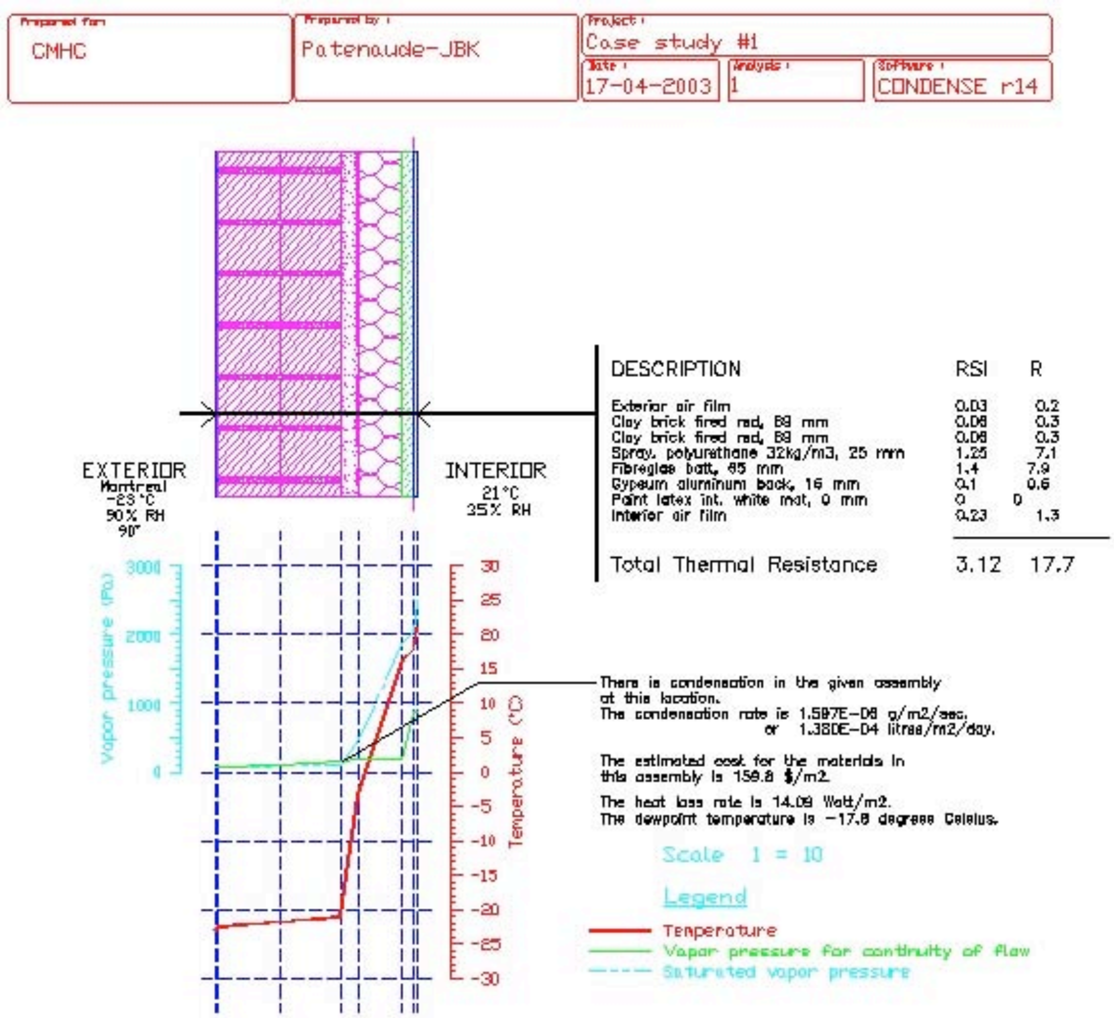
SIM-1

Modeling of the original wall composition was then repeated assuming an interior relative humidity of 20% (see SIM-1A below). Under this modified design condition, the simulation showed that no condensation would form within the wall assembly.

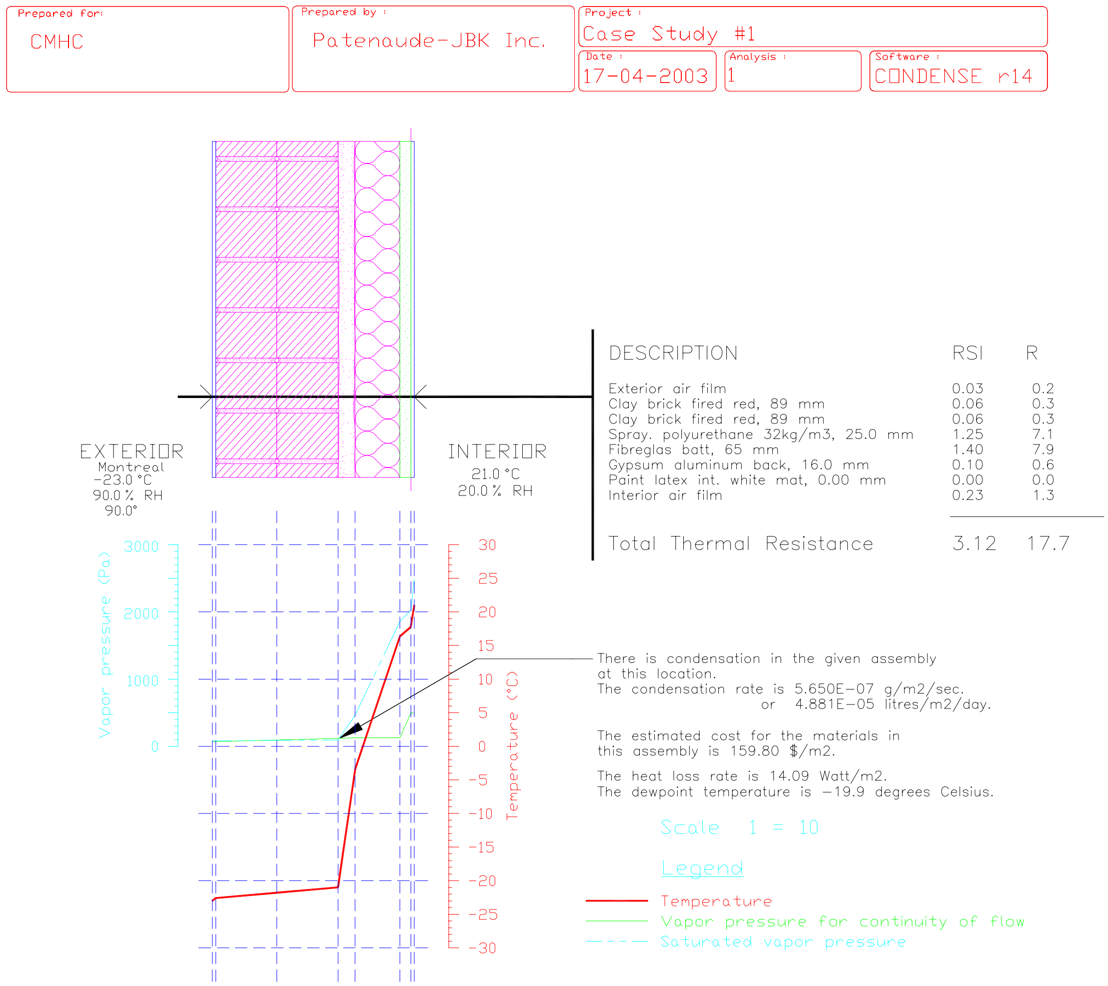


SIM-1A

Two computer models with CONDENSE of the retrofit wall assembly of this building was also conducted with the interior relative humidity set at 35% RH (*SIM-1R(35)*) and at 20%RH (*SIM-1R(20)*) respectively. The models calculated the thermal resistance of the wall to be R17.7 (RSI 3.12). Dew point temperatures of -17.8 deg Celsius and minus -19.9 deg Celsius, were calculated respectively. At 35% interior relative humidity, a condensation rate of 0.13 milliliters/m^2/day was identified within the assembly at a point along the inside face of the clay brick. At 20% interior relative humidity, a condensation rate of 0.04 milliliters/m^2/day was identified within the assembly at a point along the inside face of the clay brick. However, given that the rate of condensation produced in both cases is minimal, it is assumed that this idealized condition shall likely not produce any visible signs of masonry deterioration or damage to the interior finishing unless additional moisture is carried into the wall assembly from the exterior (precipitation) and/or from humid air leakage from the interior. The average wall temperature under these retrofit conditions is minus -21 deg Celsius.



SIM-1R(35)



SIM-1R(20)

The THERM simulation below (Figure T-1) graphically illustrates the temperature of the retrofitted exterior masonry wall to range between minus -20 deg Celsius and minus -23 deg Celsius.

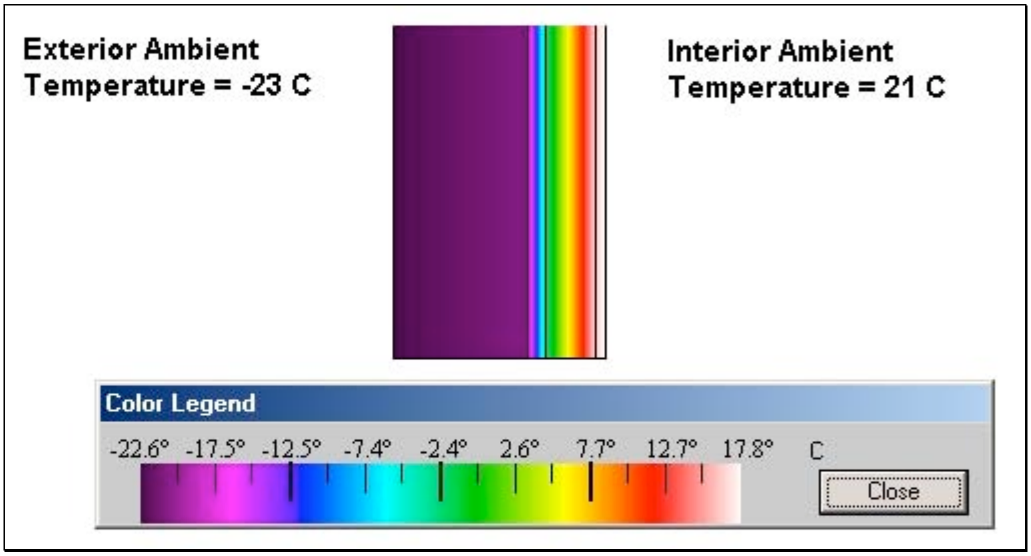


FIGURE T-1

In comparing the results of the computer modeling of both the original and the retrofit wall assemblies, it would appear to suggest that increasing the thermal resistance along the inside face of the existing masonry wall could provoke conditions favorable to increasing the rate of condensation in the wall assembly under identical ambient conditions (temperature and relative humidity). However, as no visible evidence of deterioration was observed along the exterior surface of the masonry wall at the time of our review, we are unable to establish a link between insulating existing solid masonry walls and potential accelerated deterioration of the masonry walls in the short term following the retrofit. Further intrusive review and study of the building walls in subsequent visits (every 4 to 5 years) would provide further data towards predicting the medium and long term performance of insulating solid masonry walls (see section 6.0 Conclusions).

5.2 CASE STUDY #2

Location:

Montréal, Québec

Envelope description

- 4” clay brick;
- 1 - 2 courses of 8” terra cotta blocks;
- 1” plaster;
- 1” polyurethane foam insulation;
- Polyethylene membrane on 1 ¾” steel furring;
- ½” gypsum board

Initial construction: 1927

Date of retrofit: 2002

Date of Survey: February 2003

.1 General description

Case study #2 is a single 11-story building with reinforced concrete structural elements. The first- and second-story walls originally consisted of concrete stone (9”) followed by 12” terra cotta blocks, covered by a 1” layer of plaster on the interior. The remaining walls were 4” clay bricks followed by one or two courses of 8” terra cotta blocks and finished with 1” of plaster. The retrofit was to add 1” of polyurethane directly to the plaster coat on the interior surface of the masonry, followed by a polyethylene vapour barrier with gypsum board built up on 1 ¾” steel furring.

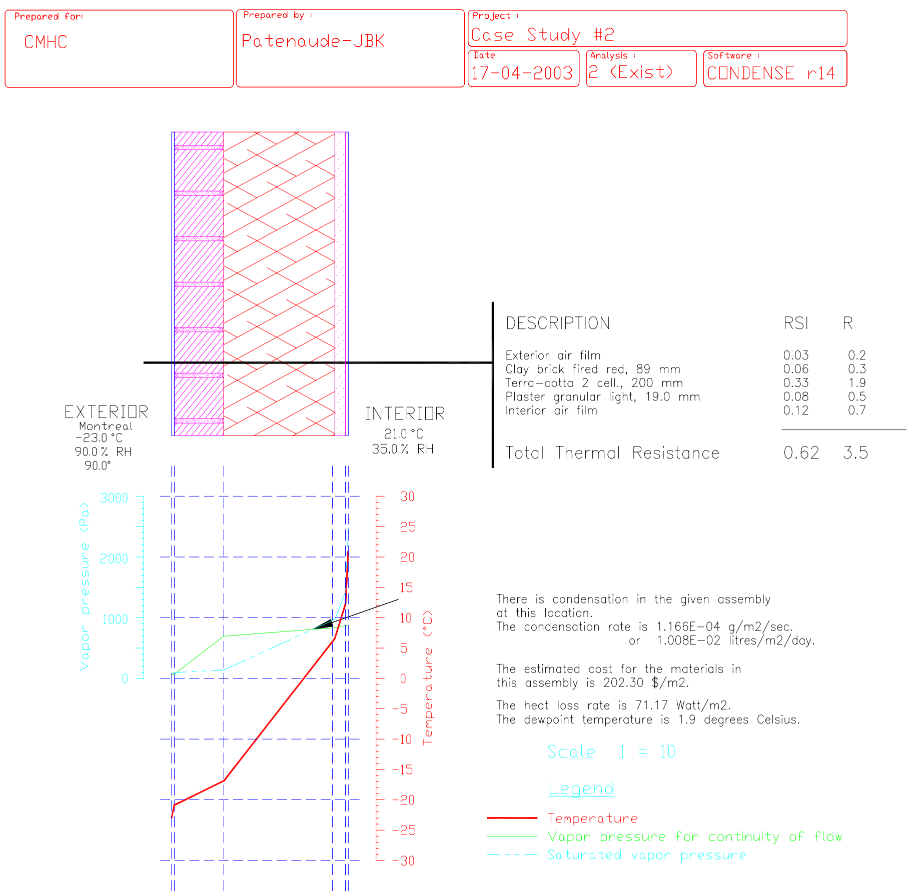
.2 Site visit observations

Upon visual inspection of the exterior, the building’s two visible façades seemed to be in fairly good condition with limited signs of degradation. There was a small amount of efflorescence noted beneath some of the windowsills, in addition to some localized dark staining along the surface of the bricks. We were unable to obtain confirmation on whether the dark staining observed was present before the retrofit. Future follow-up visits to this building will be conducted in order to assess the exterior wall condition over an extended period of time. No problems to the exterior masonry walls were reported to us during our interview with building personnel.

.3 Modeling Analysis

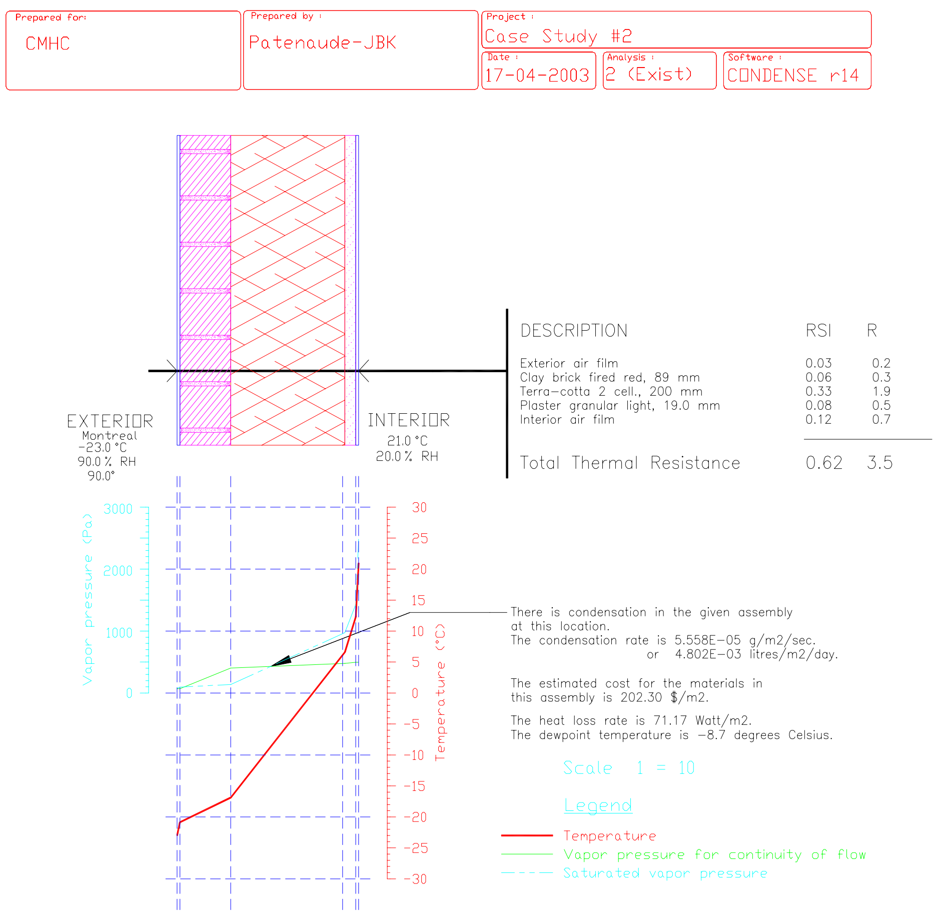
The hygrothermal simulations for Case Study #2, included the idealized modeling and comparative analysis of both the original and retrofit wall assemblies.

Using CONDENSE, the modeling of the original wall composition (see SIM-2 below) indicated that the total thermal resistance was R3.5 (RSI 0.62) and showed that a condensation rate of 10 milliliters/m^2/day would be expected to form within the terra-cotta blocks of the wall assembly under the specified design conditions. The average wall temperature under these conditions is about minus -8 deg Celsius.



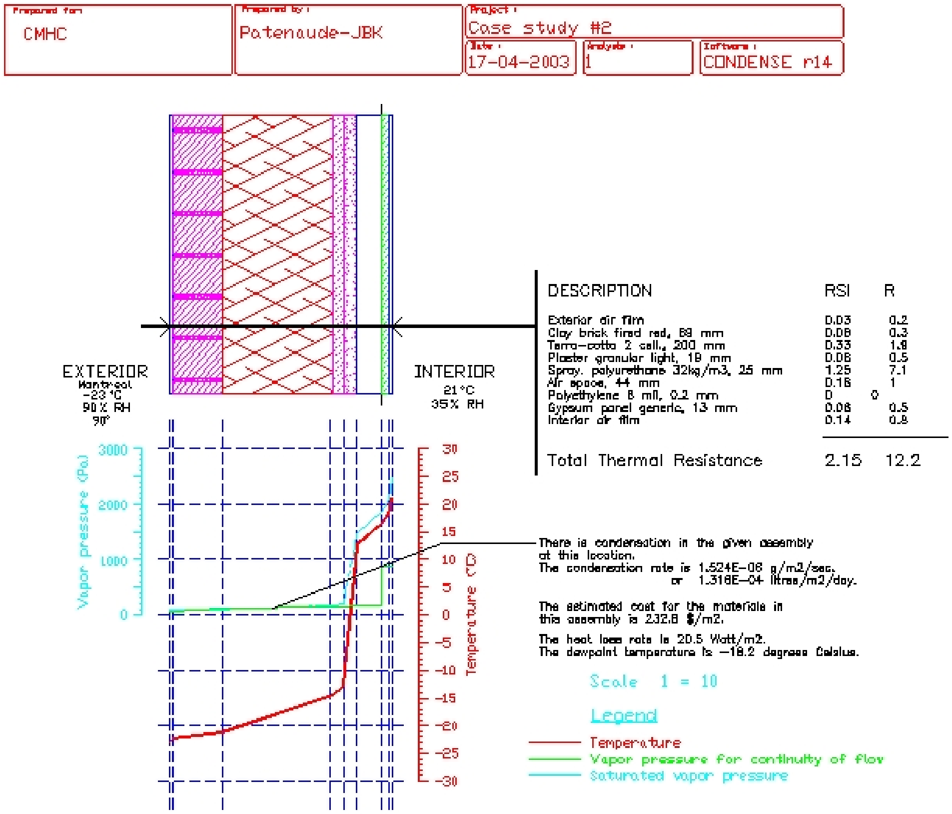
SIM-2

Modeling of the original wall composition was then repeated assuming an interior relative humidity of 20% (see SIM-2A below). Under this modified design condition, the simulation showed that a condensation rate of 4.8 milliliters/m^2/day would be expected to form within the terra-cotta blocks of the wall assembly.

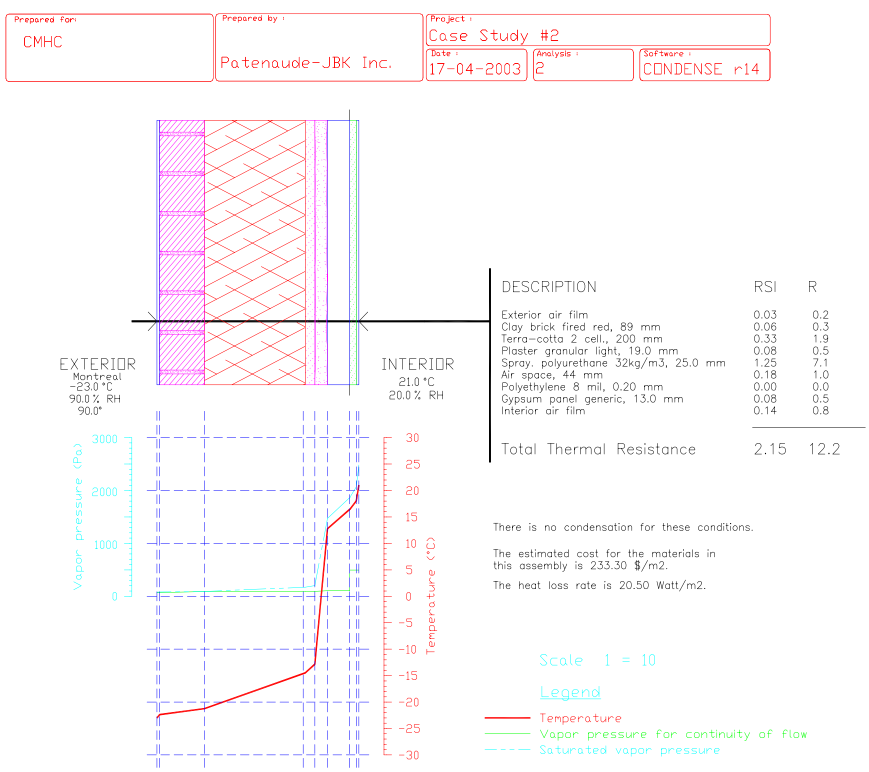


SIM-2A

For comparison, two computer models with CONDENSE of the **retrofit wall assembly** of this building was also conducted with the interior relative humidity set at both 35% RH (*SIM-2R(35)*) and 20%RH (*SIM-2R(20)*) respectively. The models calculated the thermal resistance of the wall assembly to be R12.2 (RSI 2.15).


Prepared for:
CMHC
Prepared by:
Patenaude-JBK
Project:
Case study #2
Date:
17-04-2003
Analysis:
1
Software:
CONDENSE r14
EXTERIOR
Montreal
-23 °C
90 % RH
90°
INTERIOR
21 °C
35% RH
DESCRIPTION RSI R
Exterior air film 0.03 0.2
Clay brick fired red, 89 mm 0.06 0.3
Terra-cotta 2 cell., 200 mm 0.33 1.9
Plaster granular light, 19 mm 0.08 0.5
Spray. polyurethane 32kg/m3, 25 mm 1.25 7.1
Air space, 44 mm 0.18 1
Polyethylene 8 mil, 0.2 mm 0 0
Gypsum panel generic, 13 mm 0.08 0.5
Interior air film 0.14 0.8
Total Thermal Resistance 2.15 12.2
Vapor pressure (Pa)
3000
2000
1000
0
30
25
20
15
10
5
0
-5
-10
-15
-20
-25
-30
Temperature (°C)
There is condensation in the given assembly at this location.
The condensation rate is 1.524E-08 g/m2/sec.
or 1.316E-04 litres/m2/day.
The estimated cost for the materials in this assembly is 232.8 $/m2.
The heat loss rate is 20.5 Watt/m2.
The dewpoint temperature is -18.2 degrees Celsius.
Scale 1 = 10
Legend
Temperature
Vapor pressure for continuity of flow
Saturated vapor pressure

SIM-2R(35)


Prepared For:
CMHC
Prepared by:
Patenaude-JBK Inc.
Project:
Case Study #2
Date:
17-04-2003
Analysis:
2
Software:
CONDENSE r14
EXTERIOR
Montreal
-23.0 °C
90.0 % RH
90.0°
INTERIOR
21.0 °C
20.0 % RH
DESCRIPTION RSI R
Exterior air film 0.03 0.2
Clay brick fired red, 89 mm 0.06 0.3
Terra-cotta 2 cell., 200 mm 0.33 1.9
Plaster granular light, 19.0 mm 0.08 0.5
Spray. polyurethane 32kg/m3, 25.0 mm 1.25 7.1
Air space, 44 mm 0.18 1.0
Polyethylene 8 mil, 0.20 mm 0.00 0.0
Gypsum panel generic, 13.0 mm 0.08 0.5
Interior air film 0.14 0.8
Total Thermal Resistance 2.15 12.2
Vapor pressure (Pa)
3000
2000
1000
0
30
25
20
15
10
5
0
-5
-10
-15
-20
-25
-30
Temperature (°C)
There is no condensation for these conditions.
The estimated cost for the materials in this assembly is 233.30 $/m2.
The heat loss rate is 20.50 Watt/m2.
Scale 1 = 10
Legend
Temperature
Vapor pressure for continuity of flow
Saturated vapor pressure

SIM-2R(20)

At 35% interior relative humidity a dew point temperature of -18.2 deg Celsius with a condensation rate of 0.13 milliliters/m^2/day was identified within the terra-cotta blocks of the retrofit wall assembly. At 20% interior relative humidity, no condensation within the retrofit wall assembly was identified. The average wall temperature under these retrofit conditions is about minus -17.5 deg Celsius.

The THERM simulation of the retrofit wall assembly below (Figure T-2) also graphically illustrates the temperature of the exterior masonry and terra-cotta blocks to range between minus -12 deg Celsius and minus -23 deg Celsius.

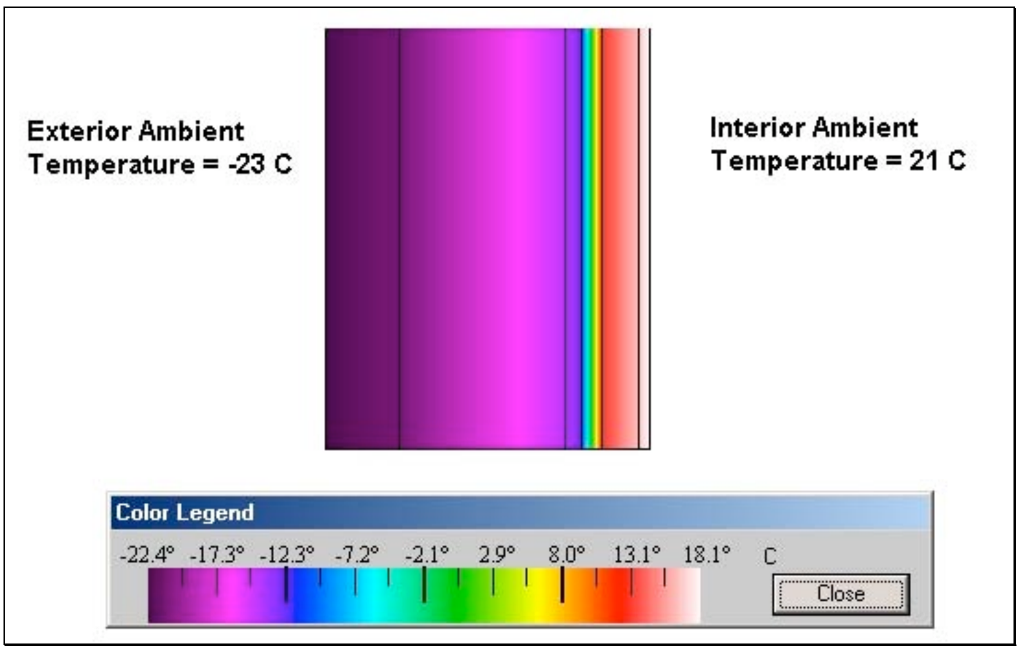
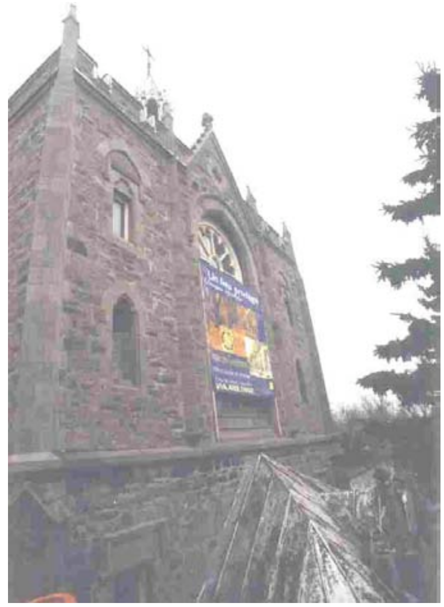


FIGURE T-2

In comparing the results of the computer modeling of both the original and the retrofit wall assemblies, it would appear to suggest that increasing the thermal resistance along the inside face of the existing masonry wall reduced conditions favorable to the formation of condensation in the wall assembly under identical ambient conditions (temperature and relative humidity).

Given as well, that no visible evidence of deterioration was observed along the exterior surface of the masonry wall at the time of our review, we are unable to establish a link between insulating existing solid masonry walls and potential accelerated deterioration of the masonry walls in the short term following the retrofit. Further intrusive review and study of the building walls in subsequent visits (every 4 to 5 years) would provide further data towards predicting the medium and long term performance of insulating solid masonry walls (see section 6.0 Conclusions).

5.3 CASE STUDY #3



Location:

Montréal, Québec

Envelope description

- 28" to 38" solid stone walls;
- No insulation;
- No interior finishing

Initial construction: 1910

Date of retrofit: 2003

Date of Survey: February 2003

.1 General description

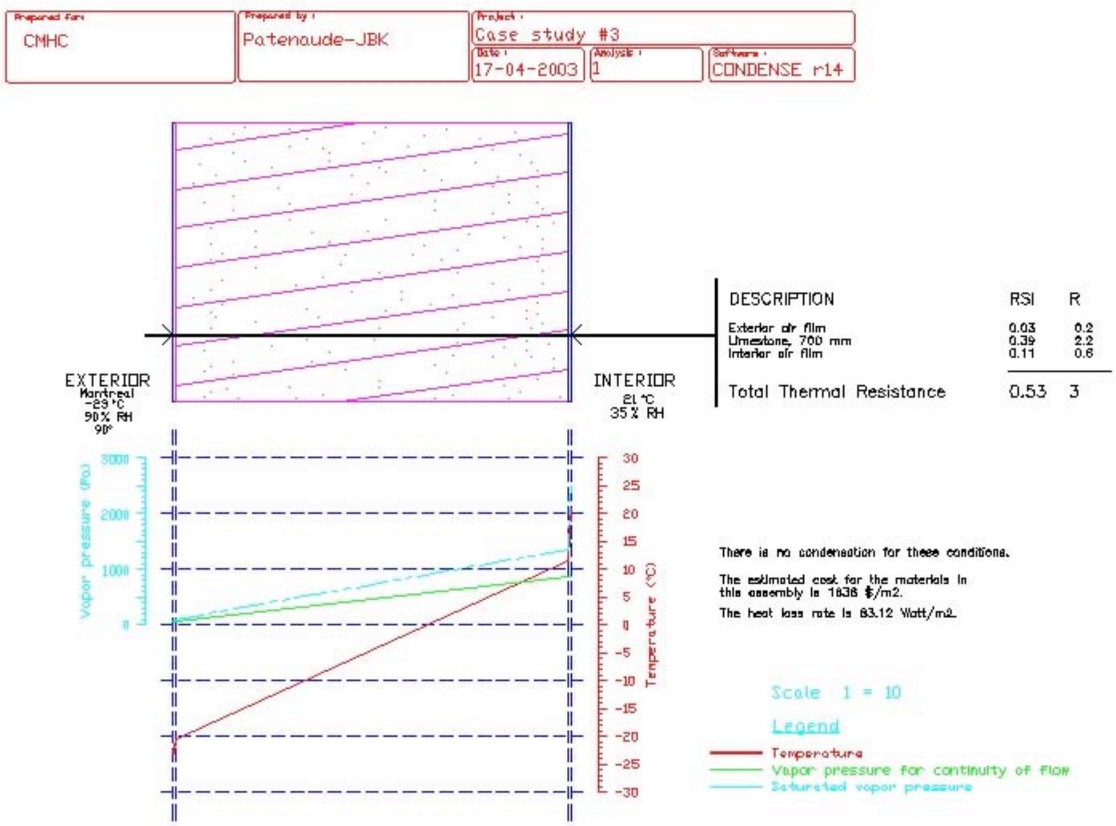
This project consists of the construction of several newer townhouse units, an underground parking lot, and an old monastic residence that was retrofitted into luxury-class condominium units. The latter is a four-storey structure that consists of load-bearing solid stone walls that vary in thickness from 28 to 38 inches. The main structural elements of the building are made of wood and steel. The vertical envelope consists only of the massive masonry walls, as it was desired to preserve the appearance of the masonry on both the interior and exterior wall surfaces. Consequently, there is no insulation and no vapour barrier system in the envelope, though particular care was taken to have a continuous air-barrier at the window-masonry joints. There was also a large section of one wall that was demolished in order to have a curtain wall system installed.

.2 Site visit observations

Many of the windows were replaced with newer aluminum frame models, but there were several cases where the wood-frame units were preserved and restored for aesthetic reasons. The masonry had been completely re-pointed and appeared to be in very good condition at the time of our survey. No noticeable deficiencies were observed. While this building has not been retrofitted with added insulation, it shall be interesting to compare rates and degree of deterioration with this exterior masonry wall, with those other buildings that have been insulated, during subsequent follow-up visits. No problems to the exterior masonry walls were reported to us during our interviews with building personnel.

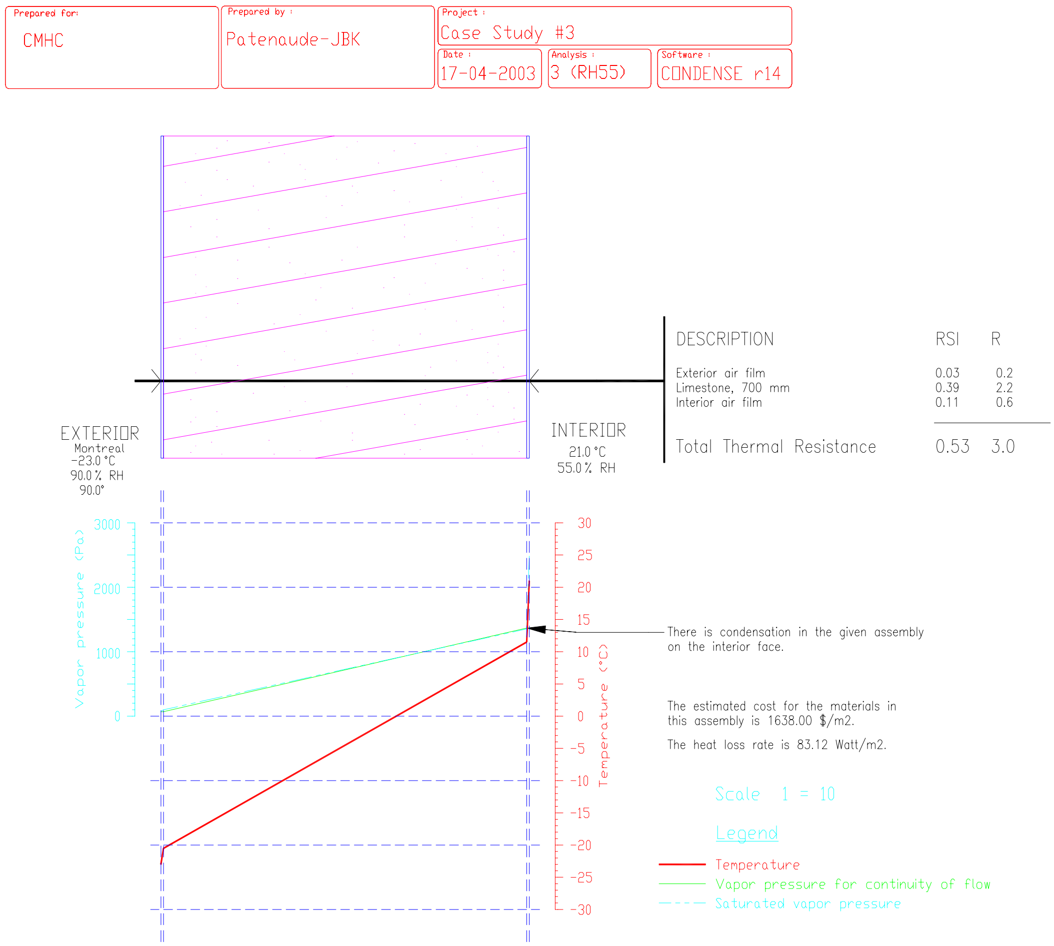
.**3 Modeling Analysis**

The computer modeling with CONDENSE of the existing wall assembly of this building shown below calculated the thermal resistance of the wall to be R3 (RSI 0.53). The average wall temperature was shown to be about minus -5 deg Celsius. No condensation based upon the input conditions for the 700mm thick limestone block walls was noted.



SIM-3(35)

However, if the interior relative humidity is increased to 55%, condensation would be expected to occur along the interior face of the limestone wall, as illustrated in model *SIM- 3(55)*, below.



SIM-3(55)

Given that no retrofit involving the addition of insulation was included in this particular case study, no additional comparative modeling using the THERM or Condense software was conducted.

5.4 CASE STUDY #4

Location:

Montréal, Québec

Envelope description

- 18" solid masonry
- 1" climate controlled air gap (see below)
- 2" glass fibre insulation in a steel stud frame
- ½" gypsum board panel

Initial construction: 1918

Date of retrofit: 2002

Date of Survey: February 2003

.1 General description

Case study #4 is a single family four-storey home built in the Westmount district of Montréal. The vertical envelope consists of the original solid masonry load-bearing walls and a steel stud partition filled with glass fibre batt insulation. The partition and the masonry are separated by a pressurized and climate controlled air gap that is monitored using a Dynamic Buffer Zone (DBZ) system. During the heating season, dry air is blown into the air gap creating a positive pressure. Since the inner partition was designed to be a continuous air barrier, it is assumed that the dry air eventually exfiltrates through and dries the exterior masonry, and hence reduces the accumulation and entrapment of moisture in the wall system.

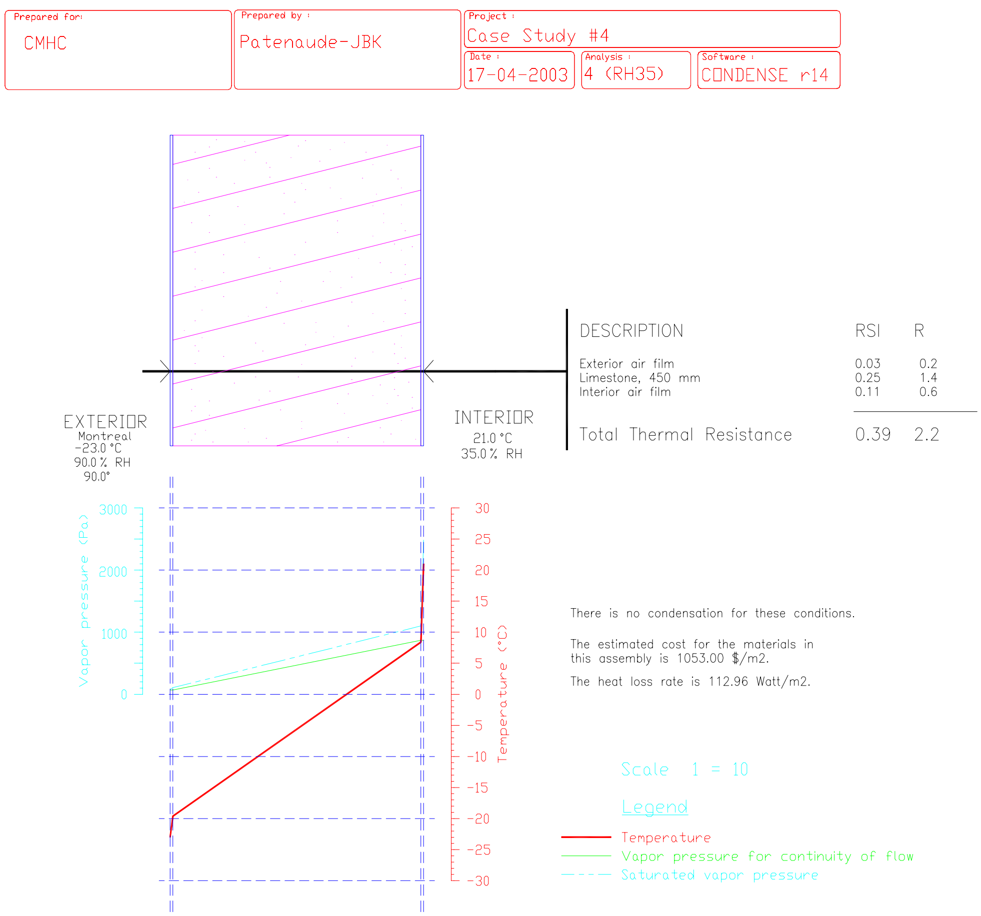
.2 Site visit observations

The DBZ system that was installed includes a computer monitoring station that detects and records wall temperatures and humidity in the air gap. The masonry of the building has recently been re-pointed and appears to be in very good condition, without any noticeable signs of deterioration. No problems to the exterior masonry walls were reported to us during our interview with the home owner.

.3 Modeling Analysis

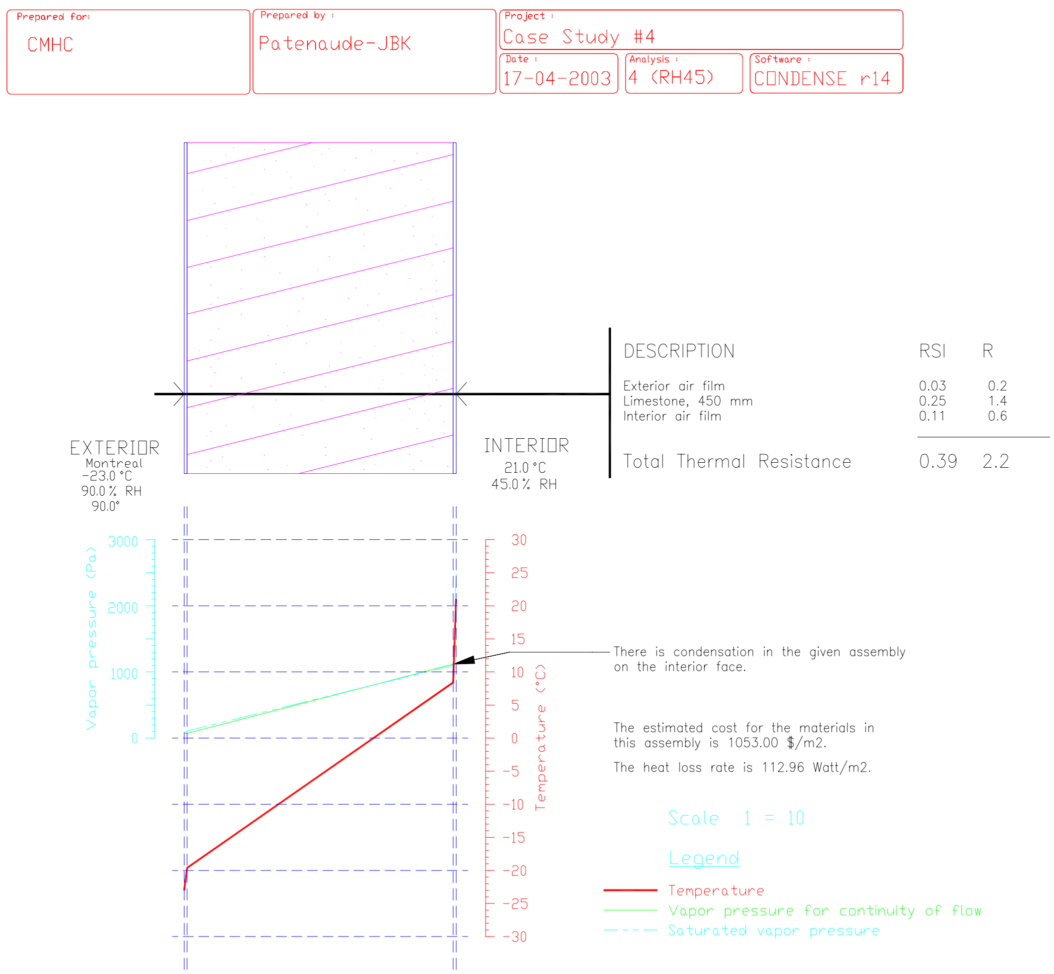
The hygrothermal simulations for Case Study #4, included the idealized modeling and comparative analysis of both the original and retrofit wall assemblies.

Using CONDENSE, the modeling of the original wall composition (see SIM-4(35) below) indicated that the total thermal resistance is R2.2 (RSI 0.39) and that average wall temperature under these conditions is about minus -5 deg Celsius. Under design conditions of 35% relative humidity within the interior of the home, no condensation would be expected within the original wall assembly.



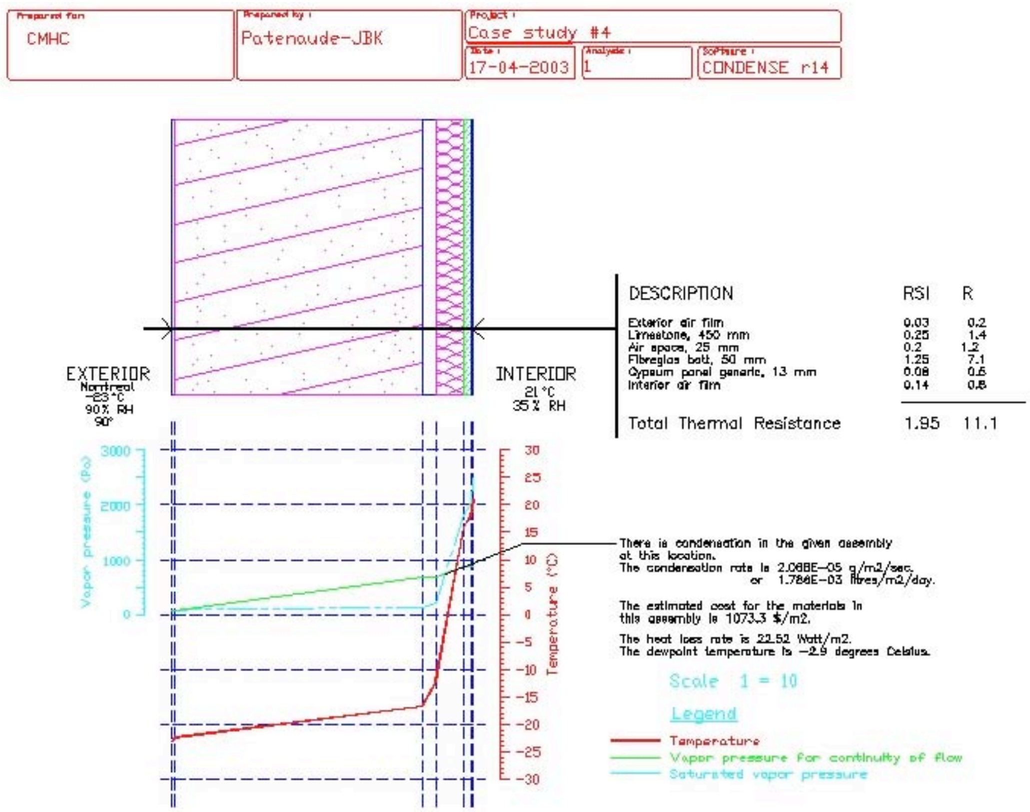
SIM-4(35)

Several models of the same wall assembly were simulated presuming interior relative humidity greater that 35%. Subsequent modeling of the original wall composition (see SIM-4(45) below) showed that condensation would begin to occur along the inside face of the exposed stone wall with an interior relative humidity of 45% or greater.



SIM-4(45)

The computer model with CONDENSE of the retrofit wall assembly of this building was conducted with the interior relative humidity set at 35% RH (*SIM-4R(35)*). The thermal resistance of the wall is R11.1 (RSI 1.95), while the average temperature within the stone wall is about minus -19 deg Celsius. A condensation rate of 1.7 milliliters/m^2/day was identified within the fiberglass batt insulation, with the dew point temperature of minus -2.9 deg Celsius.



SIM-4R(35)

The THERM simulation of the retrofit wall assembly below (Figure T-4) graphically illustrates the temperature of the exterior stone walls to range between minus -16 deg Celsius and minus -23 deg Celsius.

Therm simulation (Retrofit)

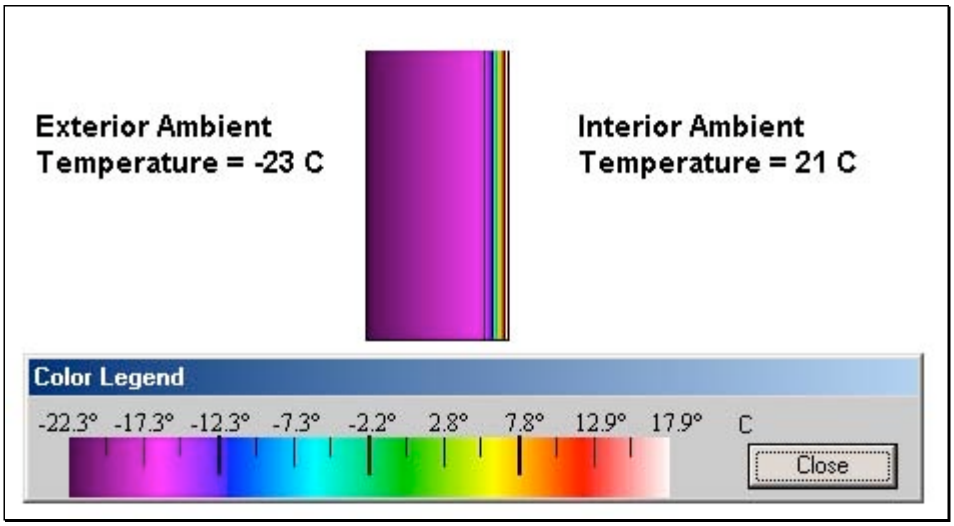


FIGURE T-4

Due to limitations of the software and data obtained, the results of the simulations provided above do not take into account the supplementary dry heating that is provided in the air space of the dynamic buffer zone design. In the static analysis, the ambient temperature within the air space is between minus -10 deg Celsius to minus -18 deg Celsius. However, we presume that the added heated dry air warms this air space, promoting a reduction of relative humidity within this cavity, and significantly increases the overall insulative resistance of the wall assembly. Depending on the effectiveness of the system it is not unrealistic to expect that the possibility of condensation within this air space is greatly reduced or eliminated entirely. Unfortunately, we were unable to obtain the data necessary regarding the temperature and relative humidity of the supplied heated air which was being exhausted into the air space at the time of our visit. As our visit coincided with the very first year of the retrofit, it is hopeful that future visits and subsequent reviews will allow for a greater understanding on the performance of this system.

5.5 CASE STUDY #5

Location:

Léry, Québec

Envelope description

- 18" to 24" limestone blocks;
- 1” polyurethane foam;
- liquid vapour barrier;
- 2” wood stud wall;
- ½” gypsum board

Initial construction: Between 1890 and 1905

Date of retrofit: 2001

Date of Survey: February 2003

General description

This single-family residence is a three-storey building made with solid stone walls and wood structural elements. Built circa 1900, the retrofit approach was to spray 1” polyurethane foam on the interior of the masonry, which would act both as insulation and as the air-barrier system. To complete the assembly a liquid vapour barrier was applied to the polyurethane to limit moisture flow into the masonry.

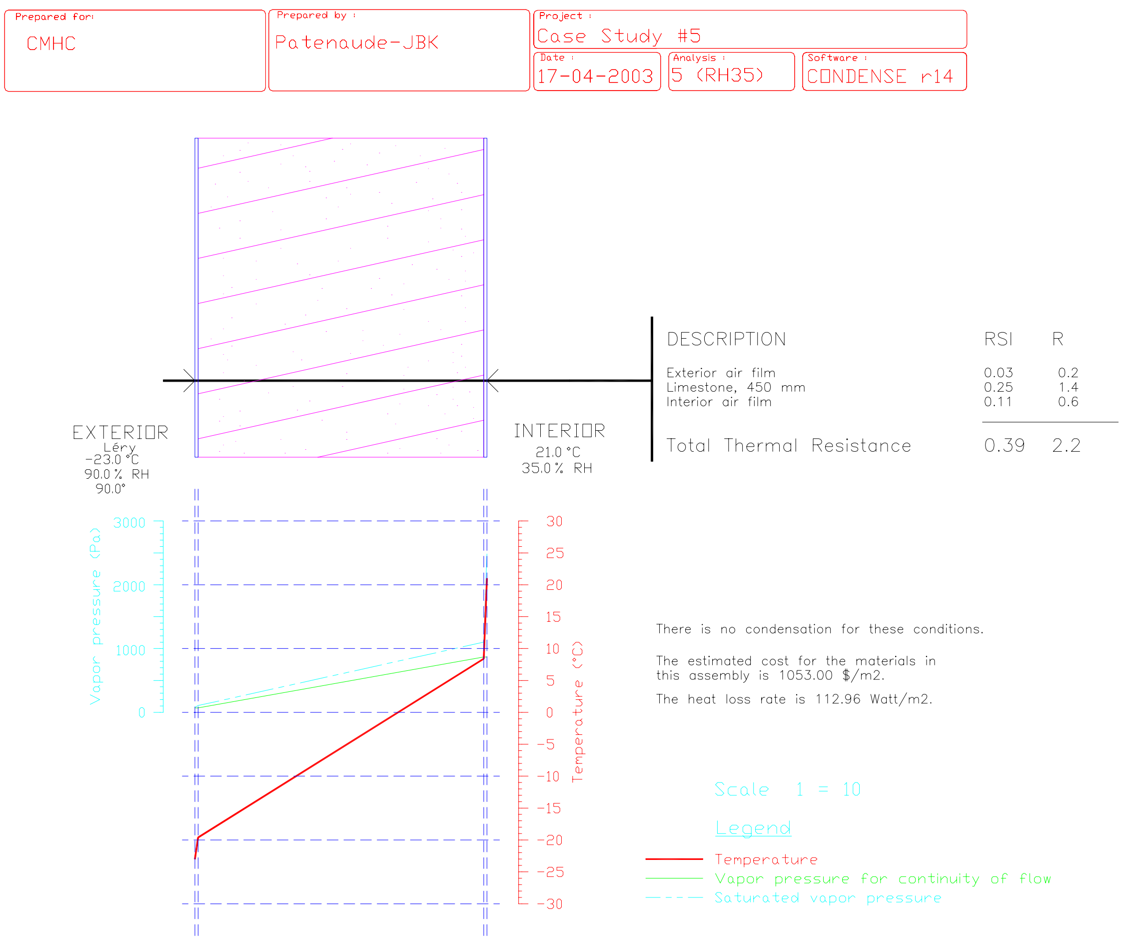
Site visit observations

The basement of the building was left un-insulated, which may cause problems in terms of different rates of thermal expansion at the joint between the insulated and un-insulated portions of the wall. No noticeable deficiencies in the exterior masonry wall were observed at the time of our survey. No problems to the exterior masonry walls were reported to us during our interview with the home owner.

.3 Modeling Analysis

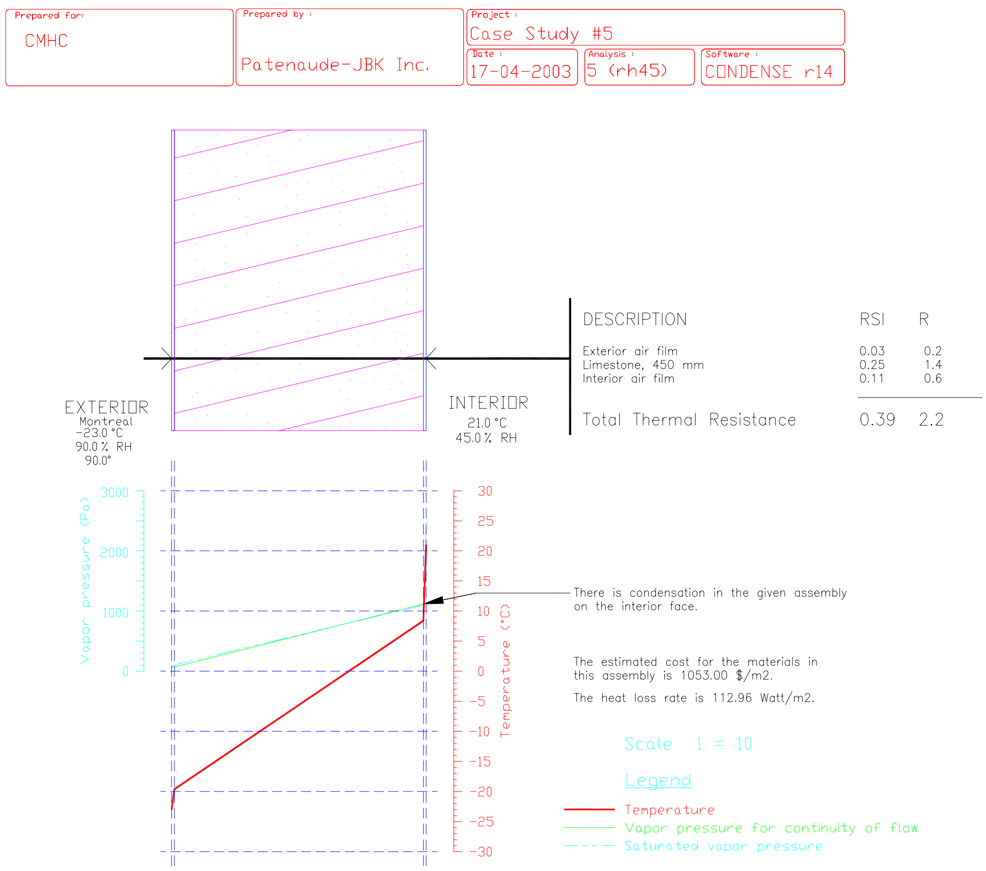
The hygrothermal simulations for Case Study #5, included the idealized modeling and comparative analysis of both the original and retrofit wall assemblies.

Using CONDENSE, the modeling of the original wall composition (see SIM-5(35) below) indicated that the total thermal resistance is R2.2 (RSI 0.39) and that average wall temperature under these conditions is about minus -5 deg Celsius. Under design conditions of 35% relative humidity within the interior of the home, no condensation would be expected within the original wall assembly.



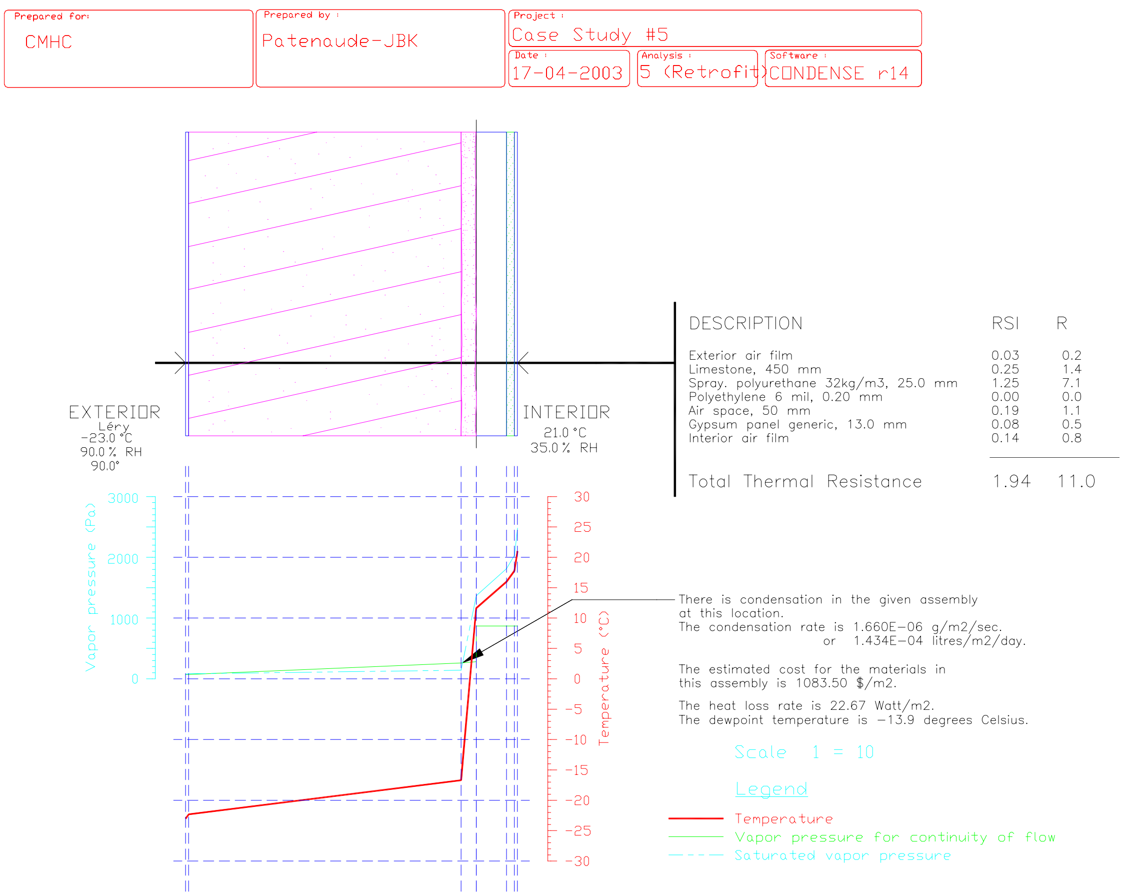
SIM-5(35)

Several models of the same wall assembly were simulated presuming interior relative humidity greater that 35%. Subsequent modeling of the original wall composition (see SIM-5(45) below) showed that condensation would begin to occur along the inside face of the exposed stone wall with an interior relative humidity of 45% or greater.



SIM-5(45)

The computer model with CONDENSE of the retrofit wall assembly of this building was conducted with the interior relative humidity set at 35% RH (*SIM-5R(35)*). The thermal resistance of the wall is R11.0 (RSI 1.94), while the average temperature within the stone wall is about minus -19 deg Celsius. A condensation rate of 0.14 milliliters/m^2/day was identified within the air space, with the dew point temperature of minus -13.9 deg Celsius.



SIM-5R(35)

The THERM simulation of the retrofit wall assembly below (Figure T-5) graphically illustrates the temperature of the exterior stone walls to range between minus -16 deg Celsius and minus -23 deg Celsius.

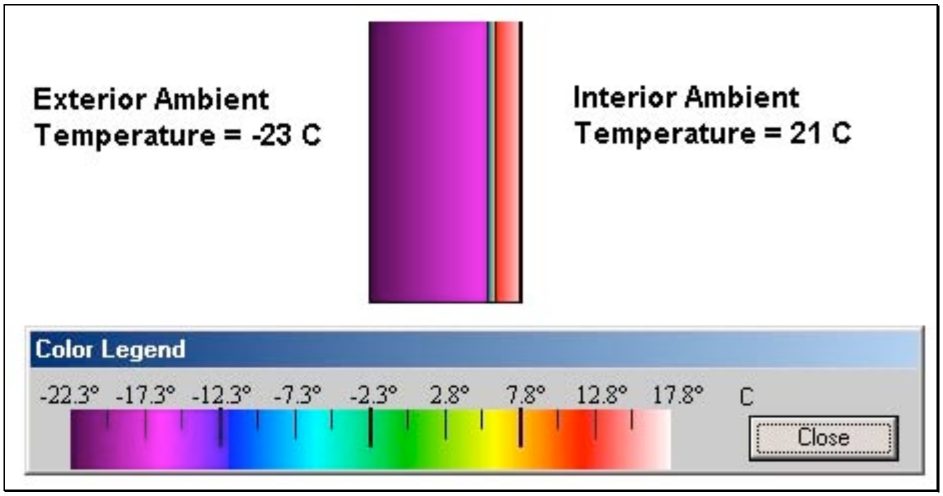


FIGURE T-5

In comparing the results of the computer modeling of both the original and the retrofit wall assemblies, it would appear to suggest that increasing the thermal resistance along the inside face of the existing masonry wall could provoke conditions favorable to increasing the rate of condensation in the wall assembly under identical ambient conditions (temperature and relative humidity).

However, as no visible evidence of deterioration was observed along the exterior surface of the masonry wall at the time of our review, we are unable to establish a link between insulating existing solid masonry walls and potential accelerated deterioration of the masonry walls in the short term following the retrofit. Further intrusive review and study of the building walls in subsequent visits (every 4 to 5 years) would provide further data towards predicting the medium and long term performance of insulating solid masonry walls (see section 6.0 Conclusions).

5.6 CASE STUDY #6

Location :

Montréal, Québec

Envelope description

- Variable brick courses;
- 1" polyurethane foam;
- steel stud wall assembly;
- ½" gypsum board

Initial construction: 1854 to 1946

Date of retrofit: 2003

Date of Survey: February 2003

.1 General description

Case Study #6 consists of ten (10) buildings that were constructed between 1854 and 1946. There are about twelve different wall compositions amongst all the buildings. The actual retrofits were dependent upon the composition of the wall (and as of April 2003 not all retrofits had commenced). In general, emphasis was placed on air- and vapour-barriers, with the inclusion of insulation in cases where the window/wall ratio was small. The insulation used was polyurethane foam.

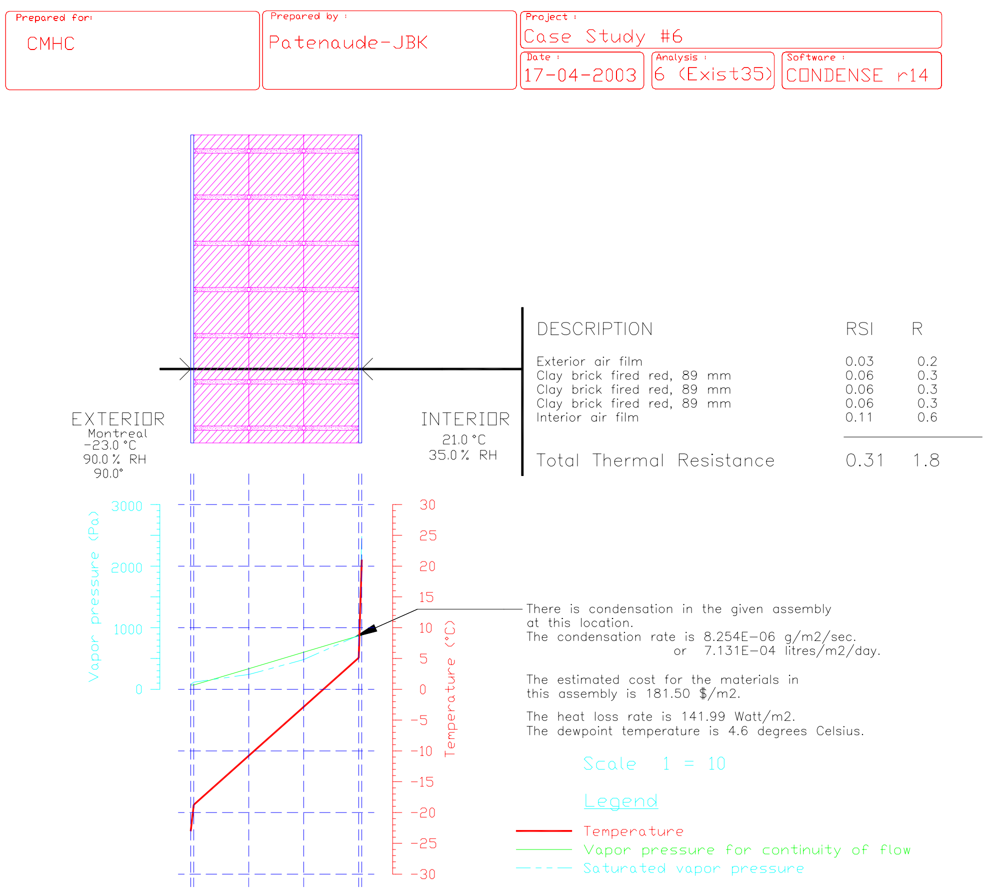
.2 Site visit observations

Many of the surrounding buildings were in a state of total disrepair. Some of the renovated units had large sections of brickwork that demanded complete replacement, which puts into question the quality of the remaining masonry. The primary building, shown in the photo above, had masonry that was in generally good condition. There were localized deficiencies that include some spalling bricks, delaminated mortar along certain brick surfaces, and some voids between the old and new layers of mortar. Future visits following retrofit work will be conducted to help to determine the performance of the new retrofitted solid masonry exterior walls. No problems to the new exterior masonry walls were reported to us during our interview with building personnel.

.3 Modeling Analysis

The hygrothermal simulations for Case Study #6, included the idealized modeling and comparative analysis of both the original and retrofit wall assemblies.

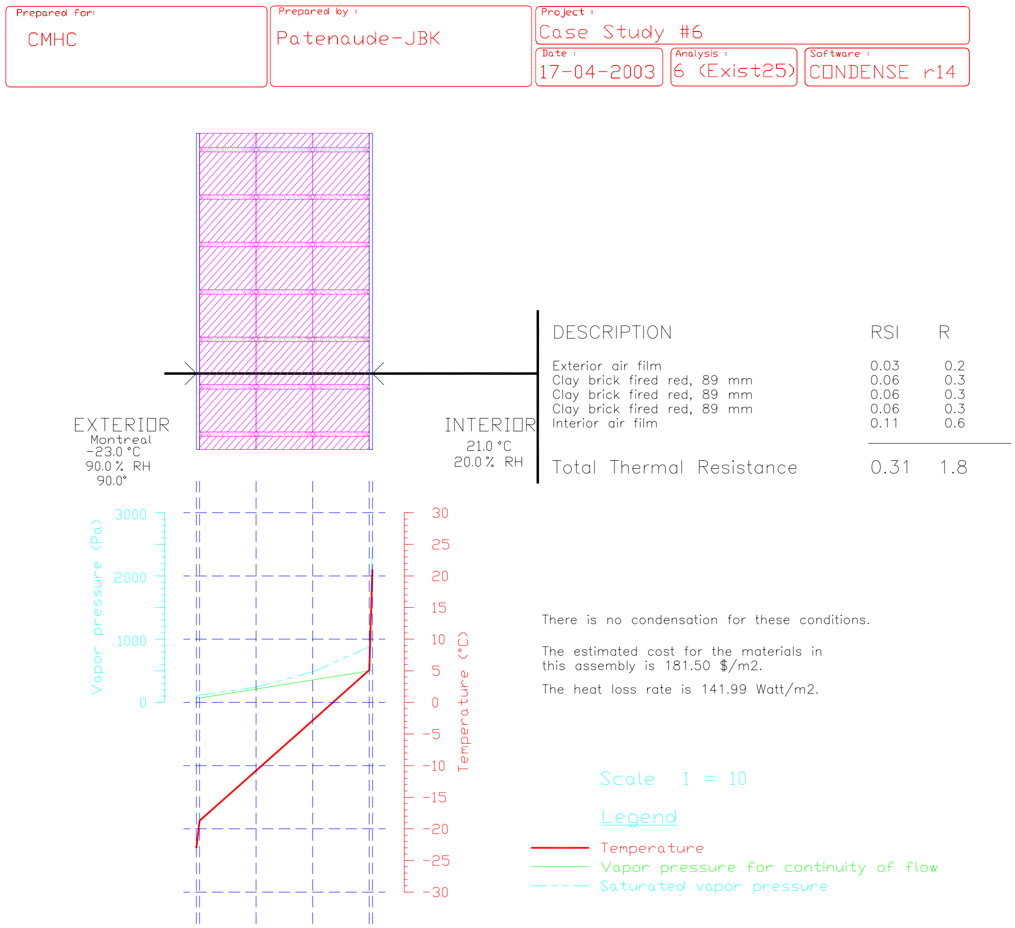
Using CONDENSE, the modeling of the original wall composition (see SIM-6(35) below) indicated that the total thermal resistance is R1.8 (RSI 0.31) and that average wall temperature under these conditions is about minus -7 deg Celsius. Under design conditions of 35% interior relative humidity, condensation would be expected to occur at a rate of condensation rate of 0.71 milliliters/m^2/day along the exposed inside face of the original wall assembly, with a dew point temperature of 4.6 deg Celsius.



SIM-6(35)

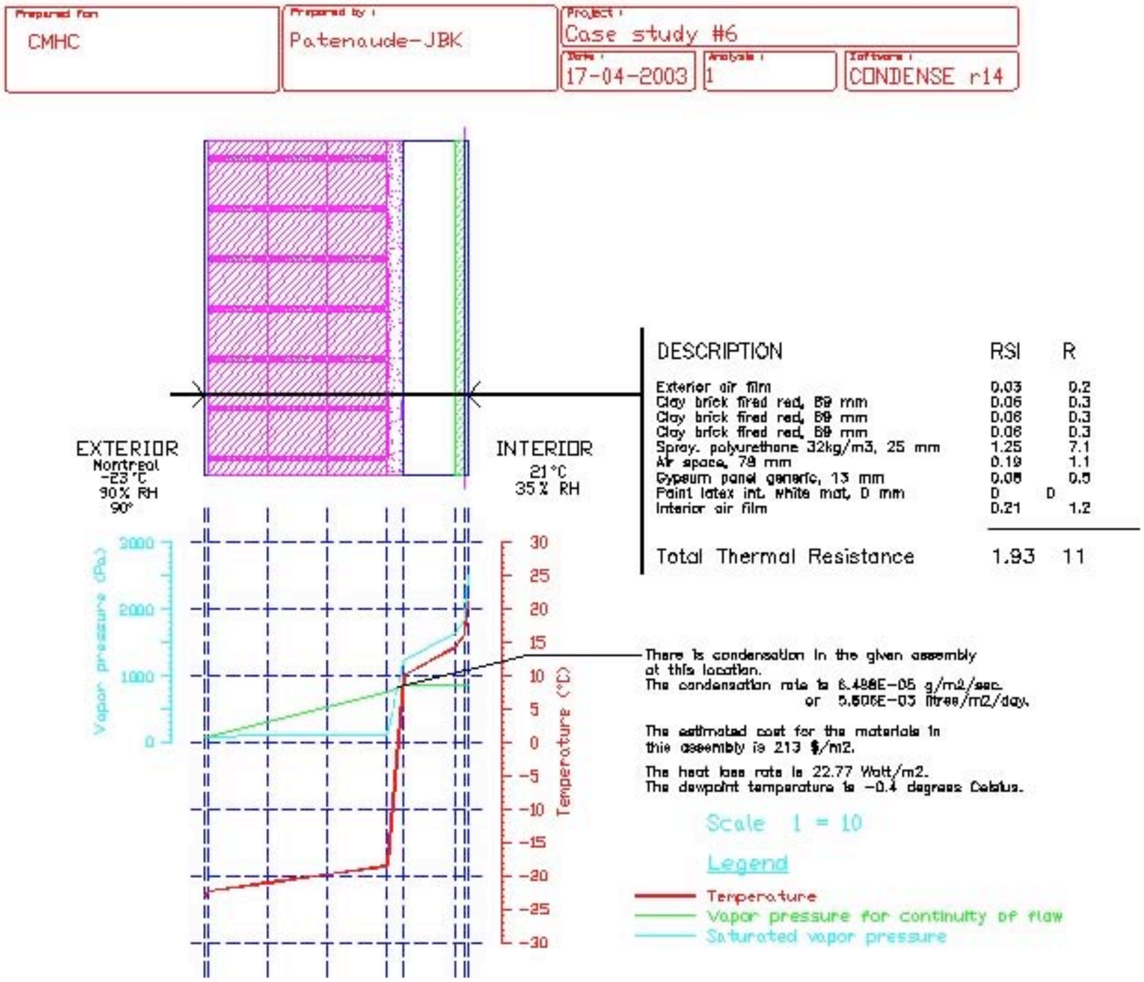
Several models of the same wall assembly were simulated presuming interior relative humidity less than 35%. Subsequent modeling of the original wall composition (see SIM-

6(20) below) showed that condensation would cease to occur presuming an interior relative humidity of 20% or less.



SIM-6(20)

The computer model with CONDENSE of the **retrofit wall assembly** of this building was conducted with the interior relative humidity set at 35% RH (*SIM-6R(35)*). The thermal resistance of the wall is R11.0 (RSI 1.93), while the average temperature within the stone wall is about minus -20 deg Celsius. A condensation rate of 5.5 milliliters/m^2/day was identified was identified within the insulation with the dew point temperature of minus -0.4 deg Celsius.



<u>SIM-6R(35)</u>

The THERM simulation of the retrofit assembly below (Figure T-6) illustrates the temperature of the exterior masonry to range between minus -18 deg Celsius and minus -23 deg Celsius.

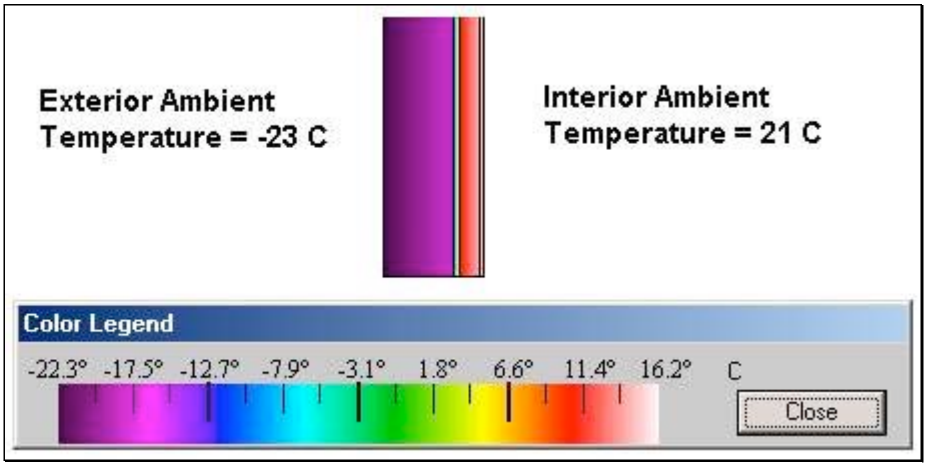


FIGURE T-6

In comparing the results of the computer modeling of both the original and the retrofit wall assemblies, it would appear to suggest that increasing the thermal resistance along the inside face of the existing masonry wall could provoke conditions favorable to increasing the rate of condensation in the wall assembly under identical ambient conditions (temperature and relative humidity).

However, as no visible evidence of deterioration was observed along the exterior surface of the masonry wall at the time of our review, we are unable to establish a link between insulating existing solid masonry walls and potential accelerated deterioration of the masonry walls in the short term following the retrofit. Further intrusive review and study of the building walls in subsequent visits (every 4 to 5 years) would provide further data towards predicting the medium and long term performance of insulating solid masonry walls (see section 6.0 Conclusions).

5.7 CASE STUDY #7

Location:

Montréal, Québec

Envelope description

- 4” fieldstone;
- 3 courses of clay brick;
- 1 ¼” polyurethane foam;
- 2 ½” steel stud frame;
- 5/8” gypsum

Initial construction: 1920

Date of retrofit: 2001

Date of Survey: February 2003

.1 General Description

This residence is a 3-storey fieldstone single-family dwelling. Originally insulated with cork panels, the interior walls were stripped down to the masonry and insulated with 1½” polyurethane foam. The assembly was completed with a steel furring frame filled with glass fibre insulation and finished with aluminum-backed gypsum board sheathing.

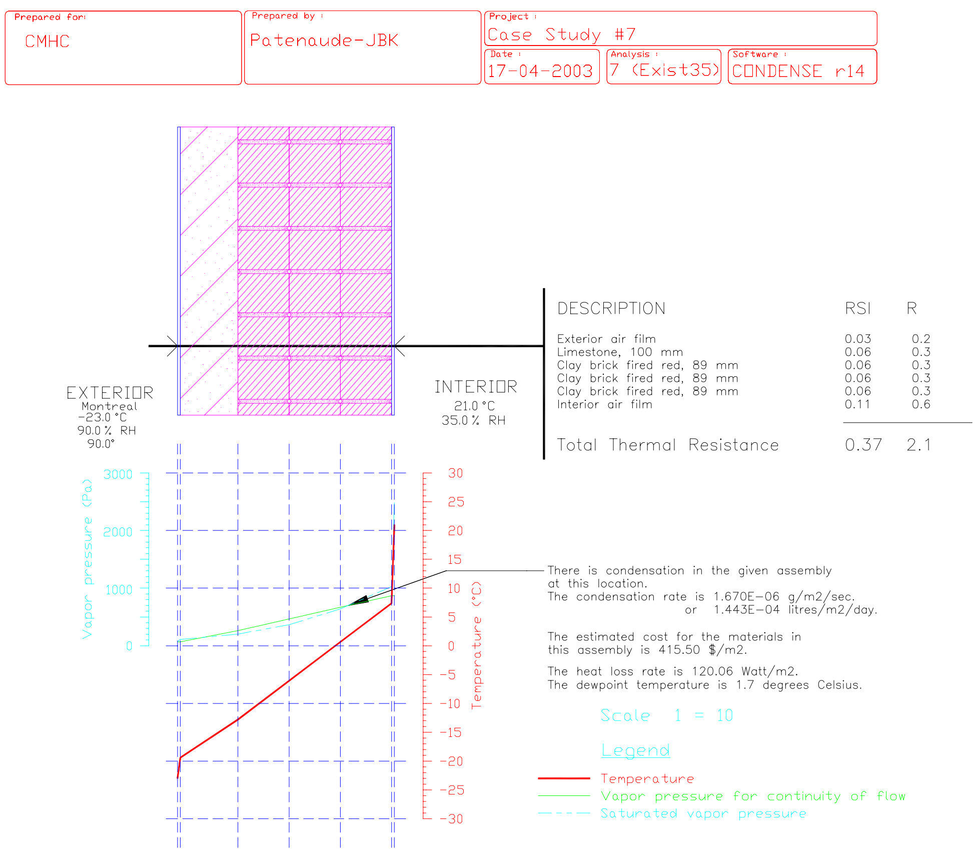
.2 Site Visit Observations

During the site visit the masonry was noted to be in very good condition with little deterioration of the mortar joints. There was no evidence of efflorescence or other outward sign of spalling. Only one relatively minor crack was noted in the masonry, which may or may not be associated with the retrofit (see photo at right). No problems to the exterior masonry walls were reported to us during our interview with the building owner.

.3 Modeling Analysis

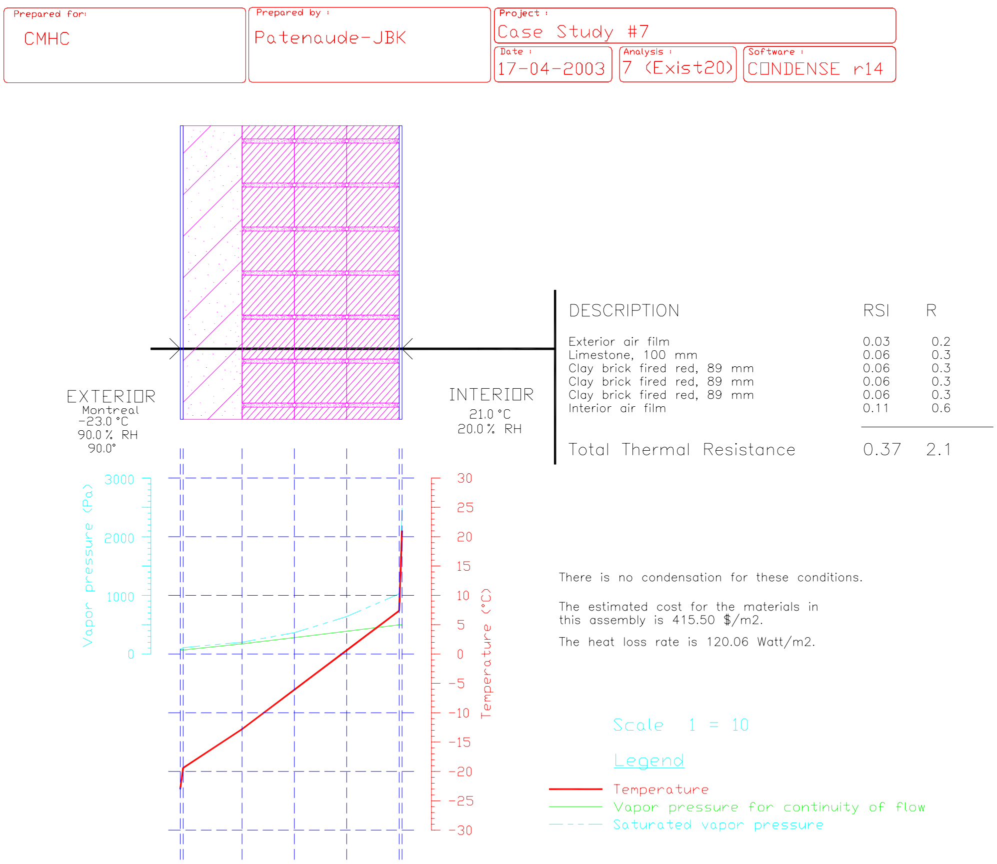
The hygrothermal simulations for Case Study # 7, included the idealized modeling and comparative analysis of both the original and retrofit wall assemblies.

Using CONDENSE, the modeling of the original wall composition (see SIM-7(35) below) indicated that the total thermal resistance was R2.1 (RSI 0.37) and that average wall temperature under these conditions is about minus -7 deg Celsius. Under design conditions of 35% interior relative humidity, condensation would be expected to occur at a rate of 0.14 milliliters/m^2/day within the clay brick assembly, with a dew point temperature of 1.7 deg Celsius.



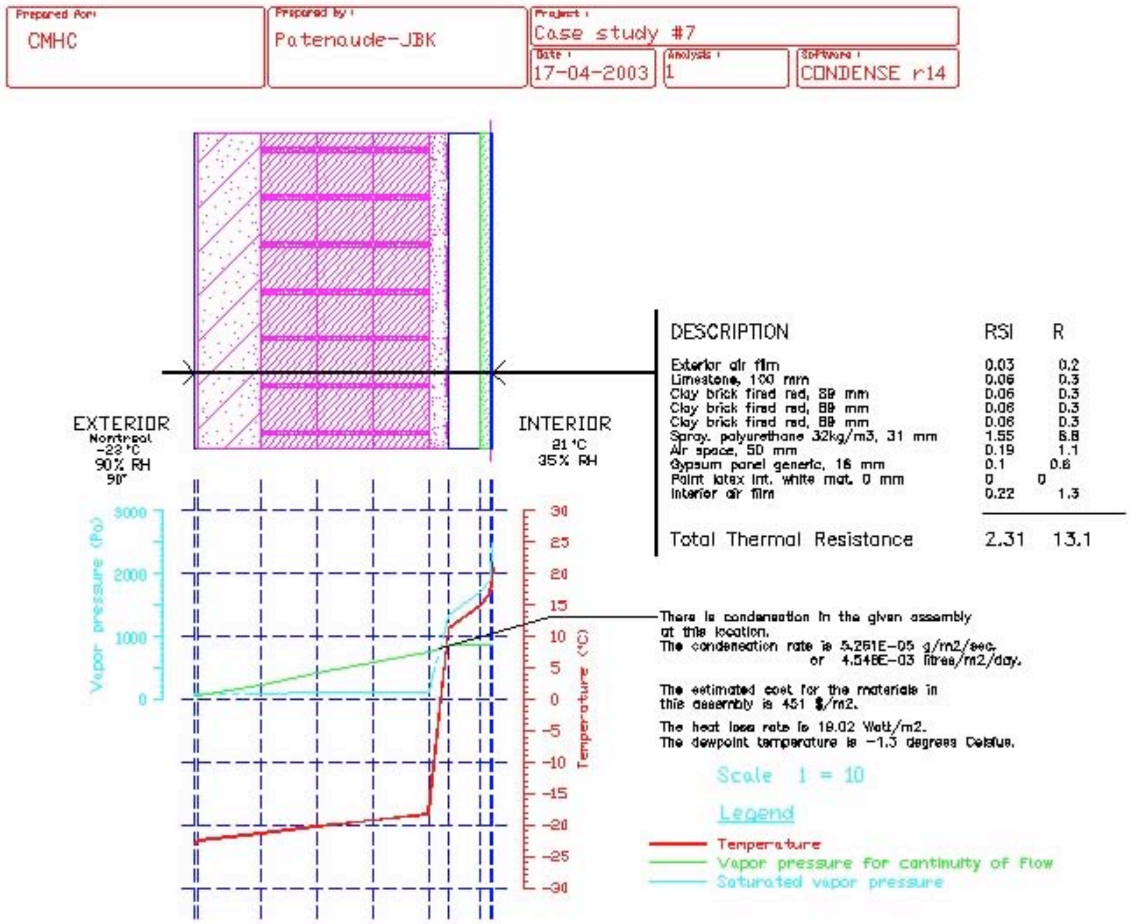
SIM-7(35)

Several models of the same wall assembly were simulated presuming interior relative humidity less than 35%. Subsequent modeling of the original wall composition (see SIM-7(20) below) showed that condensation would cease to occur presuming an interior relative humidity of 20% or less.



SIM-7(20)

The computer model with CONDENSE of the retrofit wall assembly of this building was conducted with the interior relative humidity set at 35% RH (*SIM-7R(35)*). The thermal resistance of the wall is R13.1 (RSI 2.31), while the average temperature within the stone wall is about minus -20 deg Celsius. A condensation rate of 4.5 milliliters/m^2/day was identified within the insulation with the dew point temperature of minus -1.3 deg Celsius.



SIM-7R(35)

The THERM simulation of the retrofit assembly below (see Figure T-7) graphically illustrates the temperature of the exterior masonry to range between minus -18 deg Celsius and minus -23 deg Celsius.

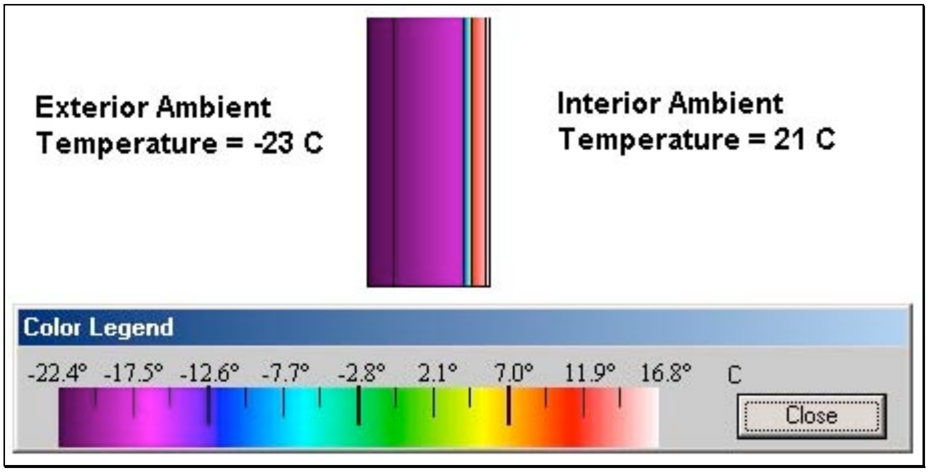


FIGURE T-7

In comparing the results of the computer modeling of both the original and the retrofit wall assemblies, it would appear to suggest that increasing the thermal resistance along the inside face of the existing masonry wall could provoke conditions favorable to increasing the rate of condensation in the wall assembly under identical ambient conditions (temperature and relative humidity).

However, as no visible evidence of deterioration was observed along the exterior surface of the masonry wall at the time of our review, we are unable to establish a link between insulating existing solid masonry walls and potential accelerated deterioration of the masonry walls in the short term following the retrofit. Further intrusive review and study of the building walls in subsequent visits (every 4 to 5 years) would provide further data towards predicting the medium and long term performance of insulating solid masonry walls (see section 6.0 Conclusions).

5.8 CASE STUDY #8

Location:

Montréal, Québec

Envelope Description

- 4” brick
- 2” air gap
- 8” concrete block
- 1 ½” polyurethane foam
- 3 ¾” steel furring
- Type 1 vapour-barrier
- ½” gypsum (interior)

Initial Construction: 1906

Date of retrofit: 1996

Date of Survey: April 2003

.1 General Description

This residential building was retrofitted in 1996 by adding 1½” polyurethane foam to the interior surface of the concrete block walls. The steel furring was built ½” into the foam and is finished with a polyethylene membrane and gypsum board panel. There are some newer sections of wall that were constructed during the retrofit that are not solid masonry, but the majority is as described above.

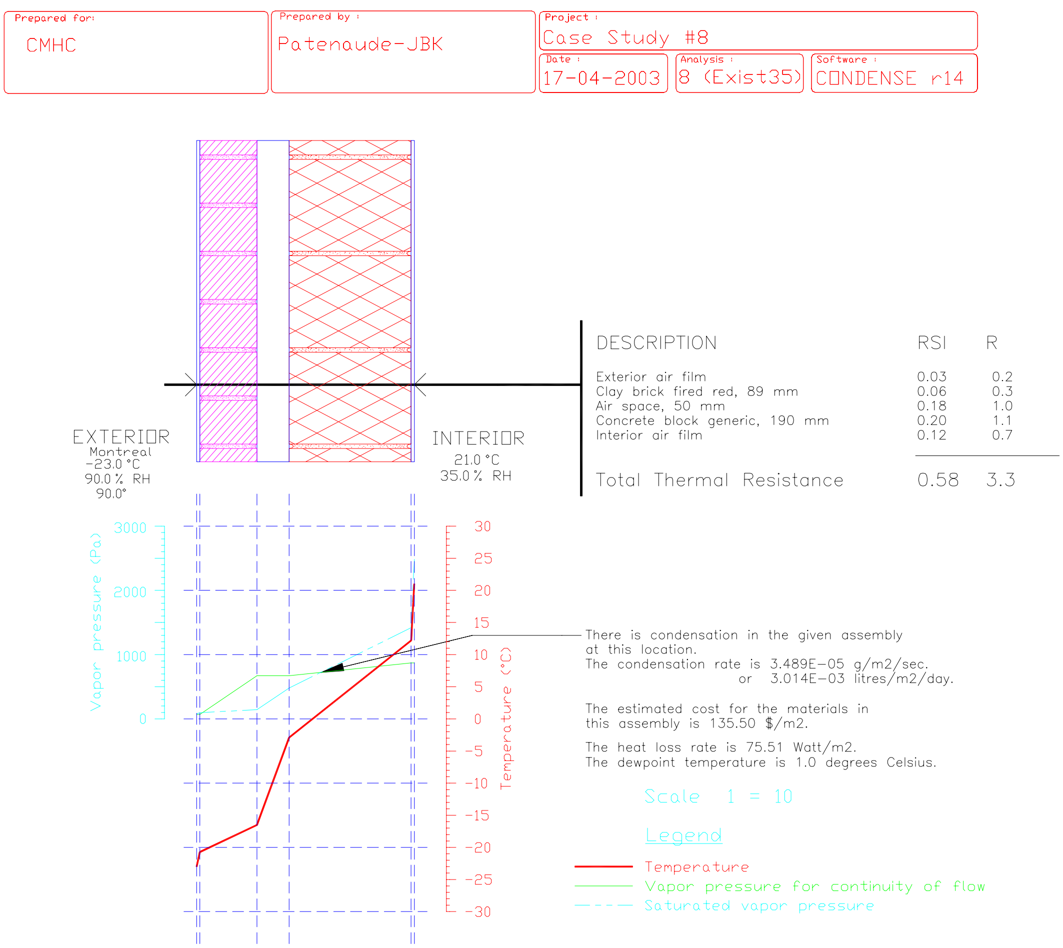
.2 Site Visit Observations

From the street-level evaluation of the masonry, it appeared that the brick façade was in very good condition and had experienced little or no degradation since the retrofit in 1996. In addition, the brick showed no signs of efflorescence or other dsymptoms of masonry deterioration. No problems to the exterior masonry walls were reported to us during our interview with building personnel.

.3 Modeling Analysis

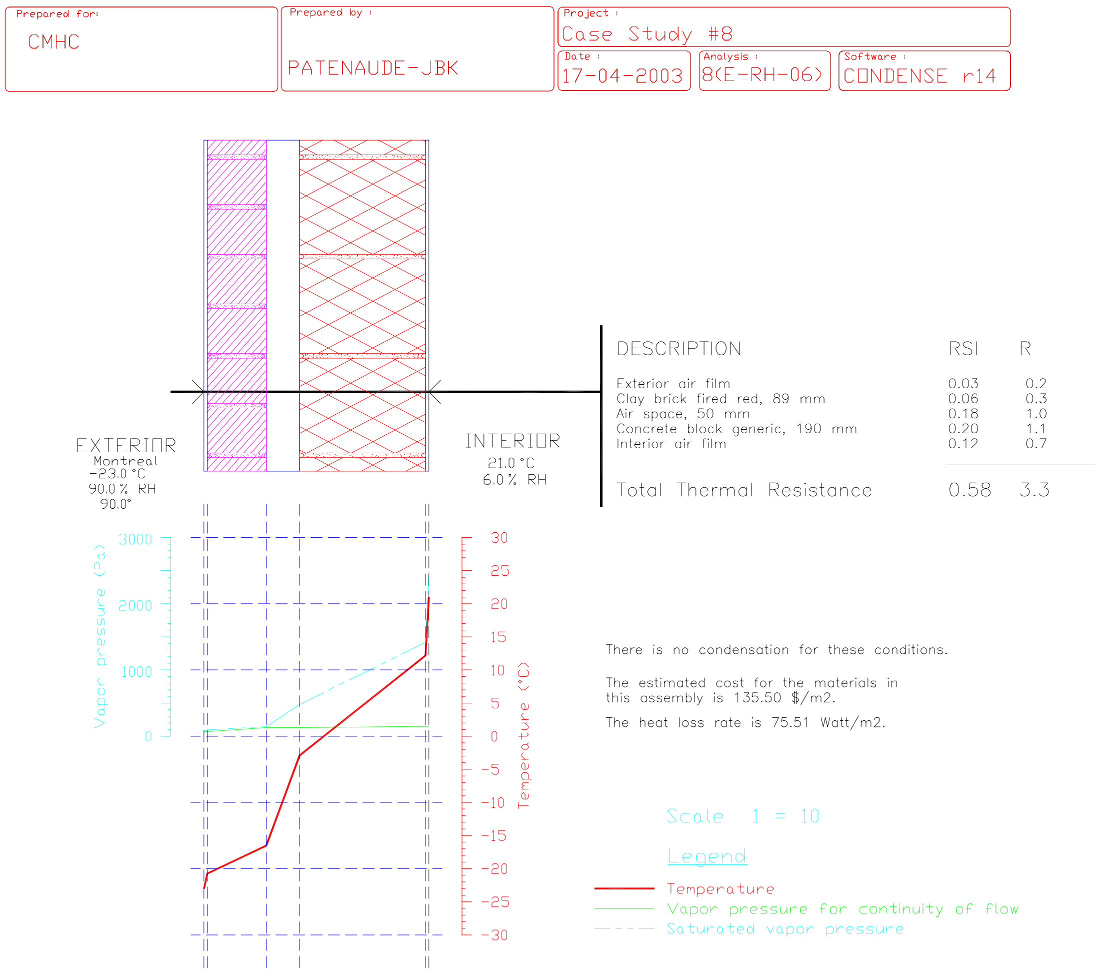
The hygrothermal simulations for Case Study # 8, included the idealized modeling and comparative analysis of both the original and retrofit wall assemblies.

Using CONDENSE, the modeling of the original wall composition (see SIM-8(35) below) indicated that the total thermal resistance was R3.3 (RSI 0.58) and that average wall temperature under these conditions is about minus -1 deg Celsius. Under design conditions of 35% interior relative humidity, condensation would be expected to occur at a rate of 3.0 milliliters/m^2/day within the concrete blocks, with a dew point temperature of 1.0 deg Celsius.



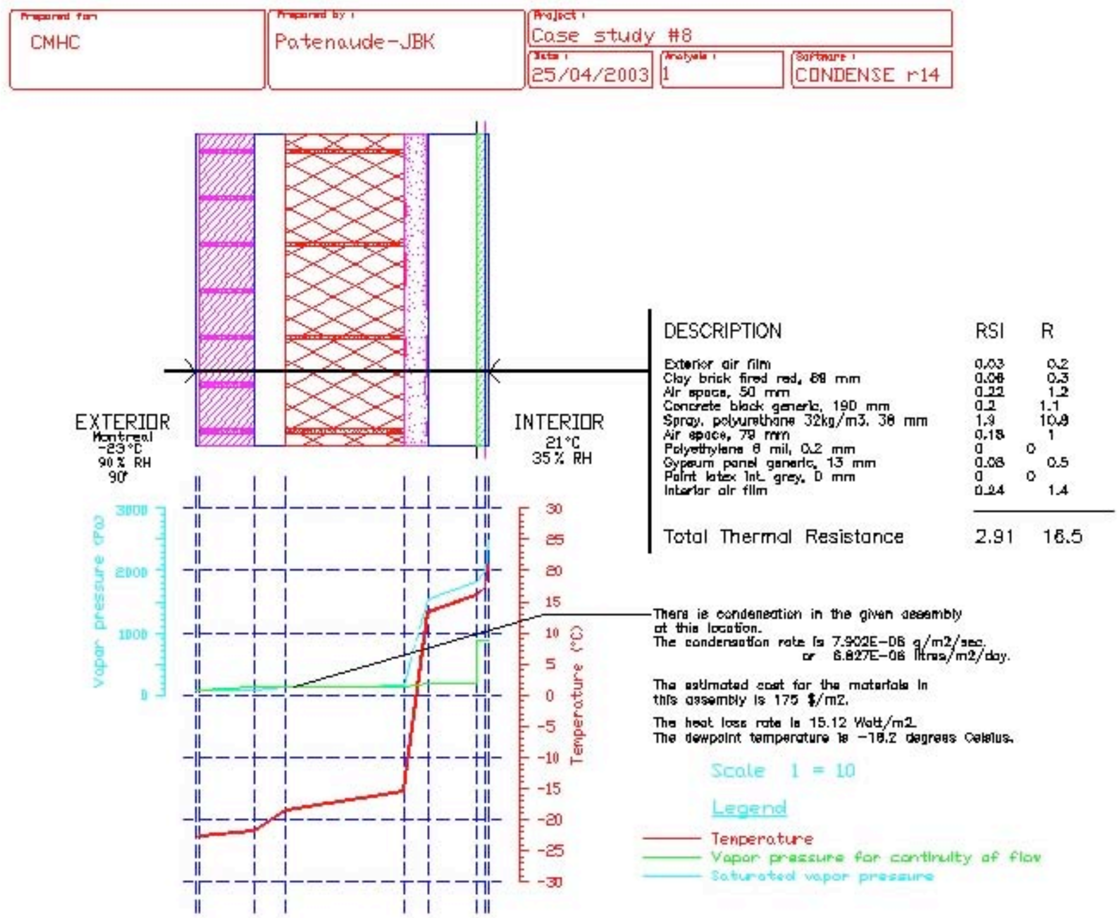
SIM-8(35)

Several models of the same wall assembly were simulated presuming interior relative humidity less than 35%. Subsequent modeling of the original wall composition (see SIM-8(06) below) showed that condensation would only cease to occur presuming an interior relative humidity of 6% or less.



SIM-8(06)

The computer model with CONDENSE of the **retrofit wall assembly** of this building was conducted with the interior relative humidity set at 35% RH (*SIM-8R(35)*). The thermal resistance of the wall is R18.5 (RSI 2.91), while the average temperature within the stone wall is about minus **-18 deg Celsius**. A condensation rate of 0.006 milliliters/m^2/day was identified within the exterior airspace, with the dew point temperature of minus -18.2 deg Celsius.



SIM-8R(35)

The THERM simulation of the retrofit assembly below (see Figure T-8) graphically illustrates the temperature of the exterior masonry to range between minus -16 deg Celsius and minus -23 deg Celsius.

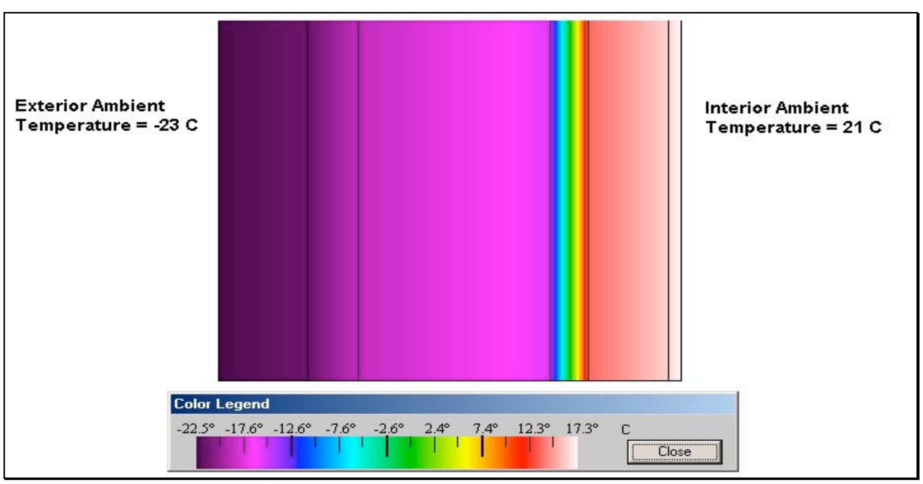


FIGURE T-8

In comparing the results of the computer modeling of both the original and the retrofit wall assemblies, it would appear to suggest that the strategy used to increase the thermal resistance along the inside face of the existing masonry wall for this case study case actually reduced the rate of condensation in the wall assembly under identical ambient conditions (temperature and relative humidity).

Given as well, that no visible evidence of deterioration was observed along the exterior surface of the masonry wall at the time of our review, we are unable to establish a link between insulating existing solid masonry walls and potential accelerated deterioration of the masonry walls in the short term following the retrofit. Further intrusive review and study of the building walls in subsequent visits (every 4 to 5 years) would provide further data towards predicting the medium and long term performance of insulating solid masonry walls (see section 6.0 Conclusions).

5.9 CASE STUDY #9

Location:

Montréal, Québec

Envelope Description

- 13" brick (3 courses)
- 1 ½" polyurethane
- 3 5/8" steel furring
- ½ " gypsum

Initial Construction: 1930

Date of Retrofit: 1999

Date of Survey: April 2003

.1 General Description

Retrofitted in 1999, this building has some newly constructed brick façades in addition to the solid brick wall described above. The general retrofit approach was to add 1½" polyurethane to the interior surface of the brick, followed by a ½" gypsum board built on steel furring. There is a 3 1/8" air gap between the gypsum and polyurethane due to the steel furring being imbedded ½" into the insulation. The building is used for residential purposes only.

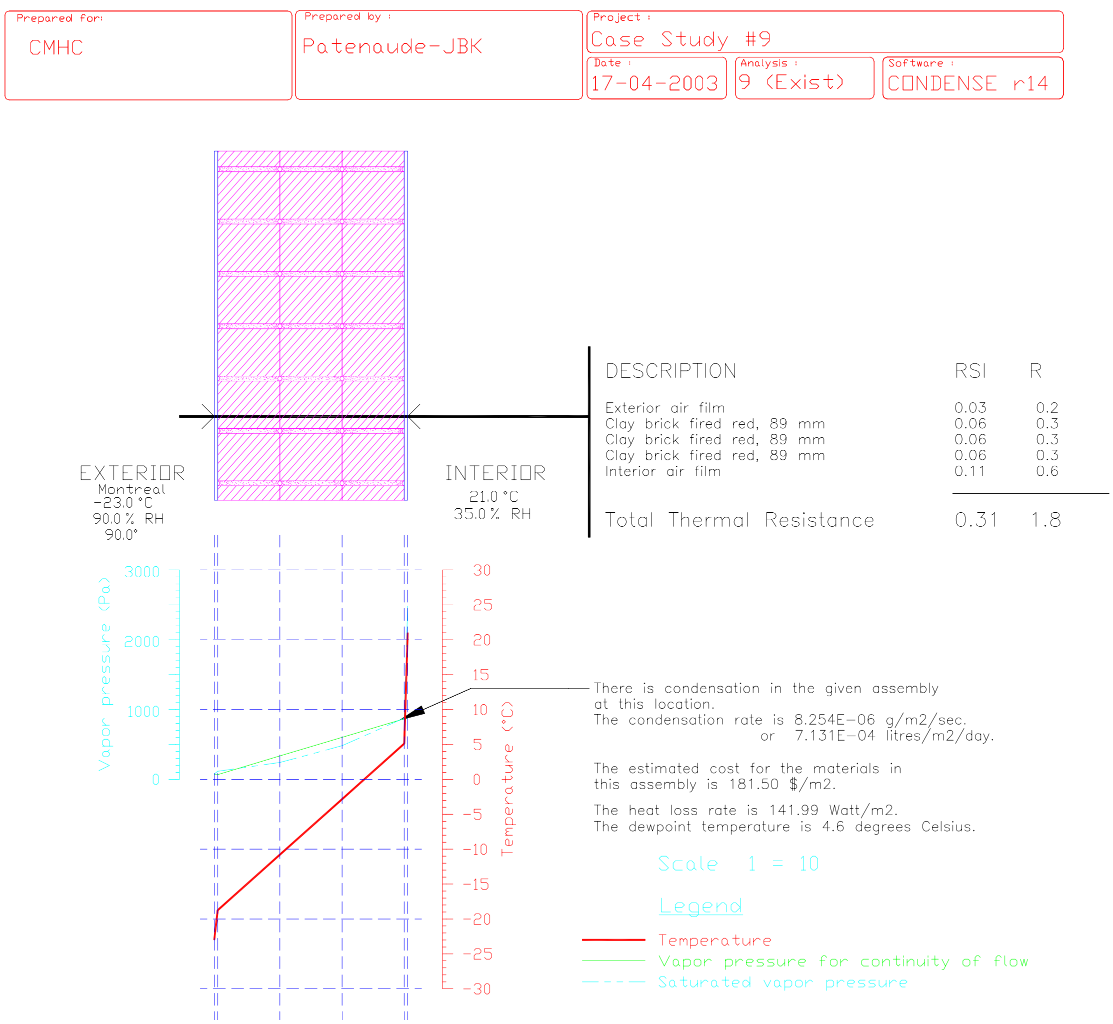
.2 Site Visit Observations

There were some small deficiencies (minor cracks and spalling) observed at the corner of the building where the eastern façade formerly joined with the adjacent building, which was demolished and rebuilt. The photo to the right shows a crack at the corner of the brickwork. These cracks may or may not be related to the insulation retrofit conducted on the building. No problems to the exterior masonry walls were reported to us during our interview with building personnel.

.3 Modeling Analysis

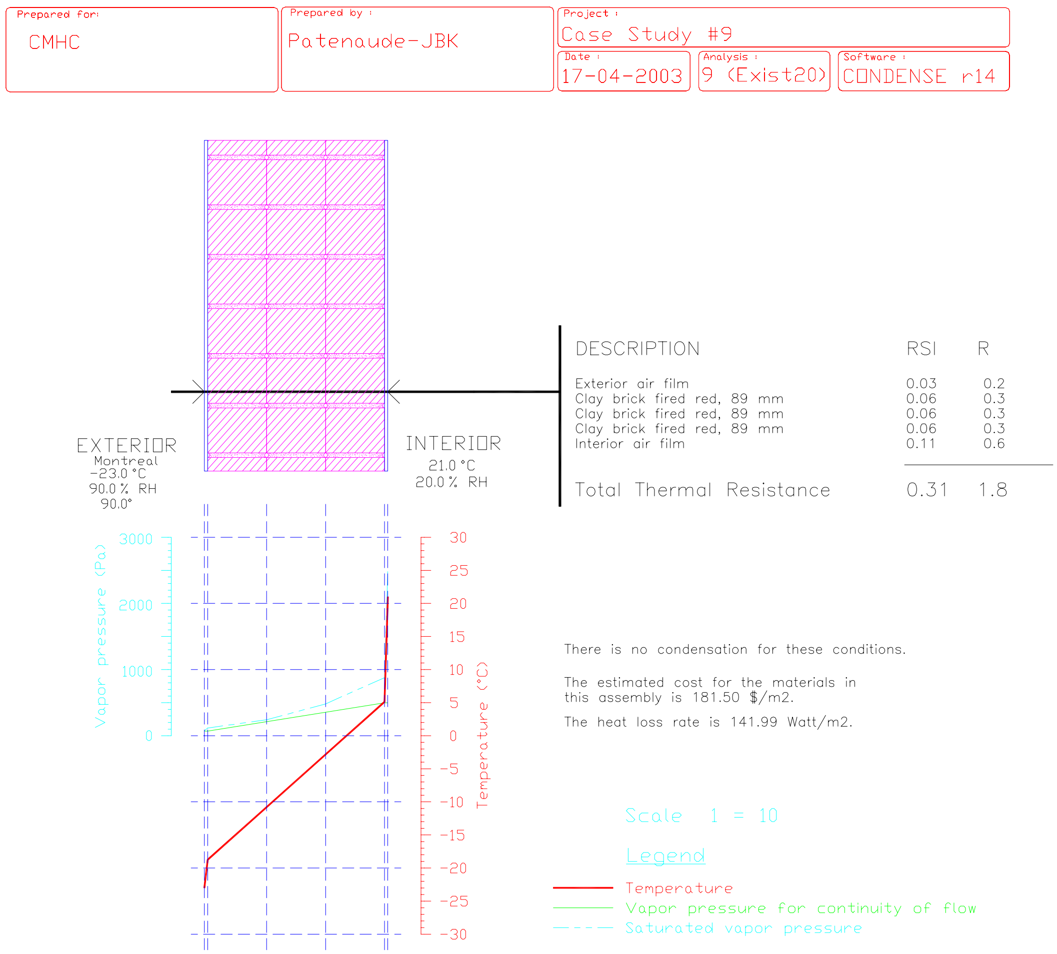
The hygrothermal simulations for Case Study # 9, included the idealized modeling and comparative analysis of both the original and retrofit wall assemblies.

Using CONDENSE, the modeling of the original wall composition (see SIM-9(35) below) indicated that the total thermal resistance was R1.8 (RSI 0.31) and that average wall temperature under these conditions is about minus -5 deg Celsius. Under design conditions of 35% interior relative humidity, condensation would be expected to occur at a rate of 0.71 milliliters/m^2/day close to the inside face of the exposed clay bricks, with a dew point temperature of 4.6 deg Celsius.



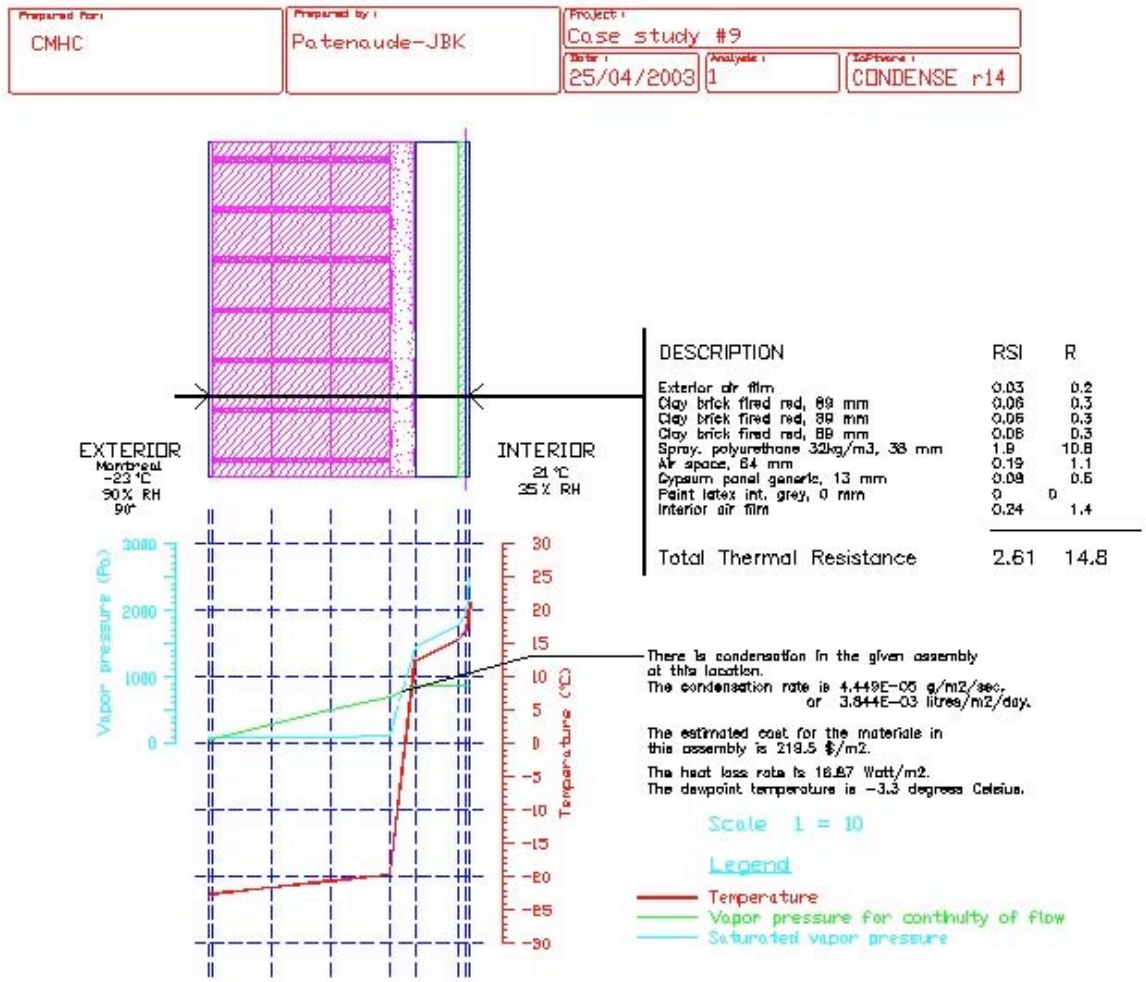
SIM-9(35)

Several models of the same wall assembly were simulated presuming interior relative humidity less than 35%. Subsequent modeling of the original wall composition (see SIM-9(20) below) showed that condensation would cease to occur presuming an interior relative humidity of 20% or less.



SIM-9(20)

The computer model with CONDENSE of the retrofit wall assembly of this building was conducted with the interior relative humidity set at 35% RH (*SIM-9R(35)*). The thermal resistance of the wall is R14.8 (RSI 2.61), while the average temperature within the stone wall is about minus -21.5 deg Celsius. A condensation rate of 3.8 milliliters/m^2/day was identified within the insulation, with the dew point temperature of minus -3.3 deg Celsius.



SIM-9(35)

The THERM simulation of the retrofit assembly below (see Figure T-9) graphically illustrates the temperature of the exterior masonry to range between minus -20 deg Celsius and minus -23 deg Celsius.

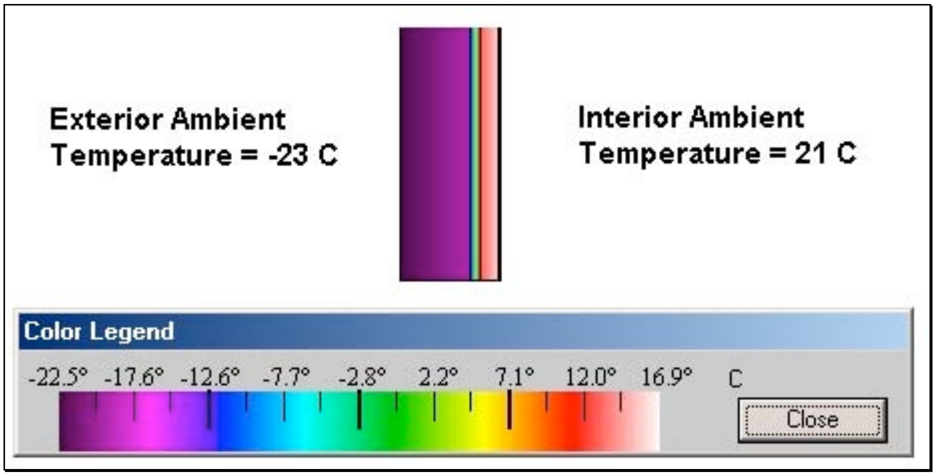


FIGURE T-9

In comparing the results of the computer modeling of both the original and the retrofit wall assemblies, it would appear to suggest that increasing the thermal resistance along the inside face of the existing masonry wall promoted conditions favorable to increasing the rate of condensation in the wall assembly under identical ambient conditions (temperature and relative humidity).

However, as no visible evidence of deterioration was observed along the exterior surface of the masonry wall at the time of our review, we are unable to establish a link between insulating existing solid masonry walls and potential accelerated deterioration of the masonry walls in the short term following the retrofit. Further intrusive review and study of the building walls in subsequent visits (every 4 to 5 years) would provide further data towards predicting the medium and long term performance of insulating solid masonry walls (see section 6.0 Conclusions).

5.10 CASE STUDY #10

Location:

Montréal, Québec

Envelope Description

- Existing stone/brick
- 1 ½" polyurethane foam insulation
- 3 5/8" air gap
- ½" gypsum

Initial construction: 1861

Date of retrofit: 2003

Date of Survey: February 2003

.1 General Description

The western façade of the building from this case study consists primarily of fieldstone blocks. Originally it was the only side exposed to the outdoor environment, but the building to the south was demolished, which revealed a second façade constructed of brick. The vertical envelope consists of the existing masonry (fieldstone on the western façade, brick on the southern) insulated with 1½" of polyurethane foam. The interior walls are finished with gypsum board on steel furring.

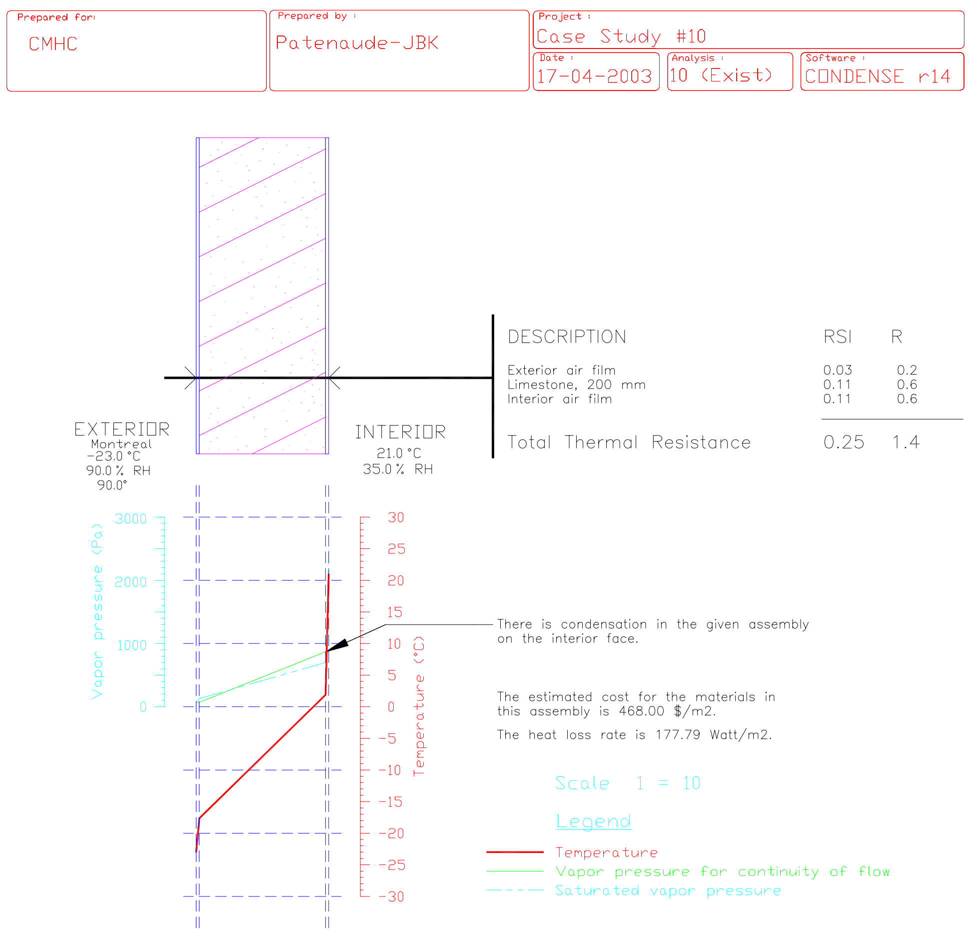
.2 Site Visit Observations

A long crack has formed at the joint of the two masonry walls, where the brick wall of the southern façade meets the fieldstone of the western façade. This cracking is likely the result of differential movement between the two different wall systems. No problems to the exterior masonry walls were reported to us during our interview with building personnel.

.3 Modeling Analysis

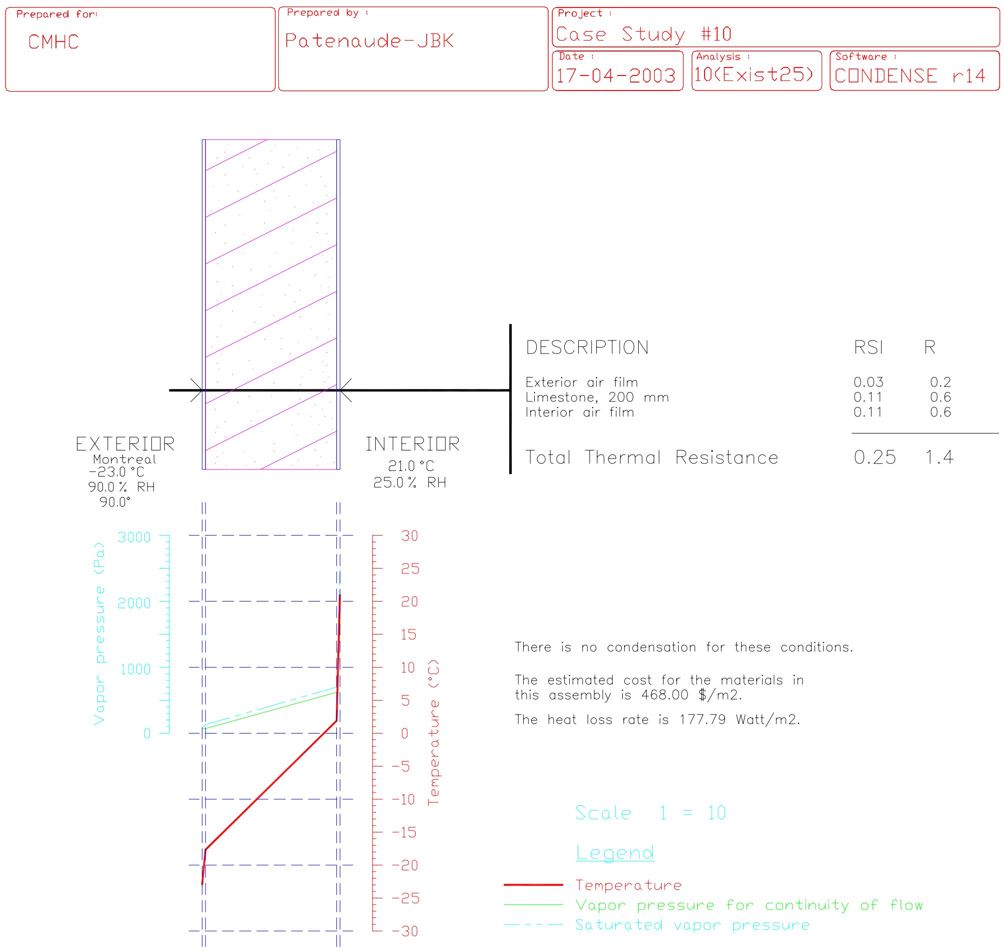
The hygrothermal simulations for Case Study # 10, included the idealized modeling and comparative analysis of both the original and retrofit wall assemblies.

Using CONDENSE, the modeling of the original wall composition (see SIM-10(35) below) indicated that the total thermal resistance was R1.4 (RSI 0.25) and that average wall temperature under these conditions is about minus -8 deg Celsius. Under design conditions of 35% interior relative humidity, condensation would be expected along the exposed interior face of the masonry wall.



SIM-10(35)

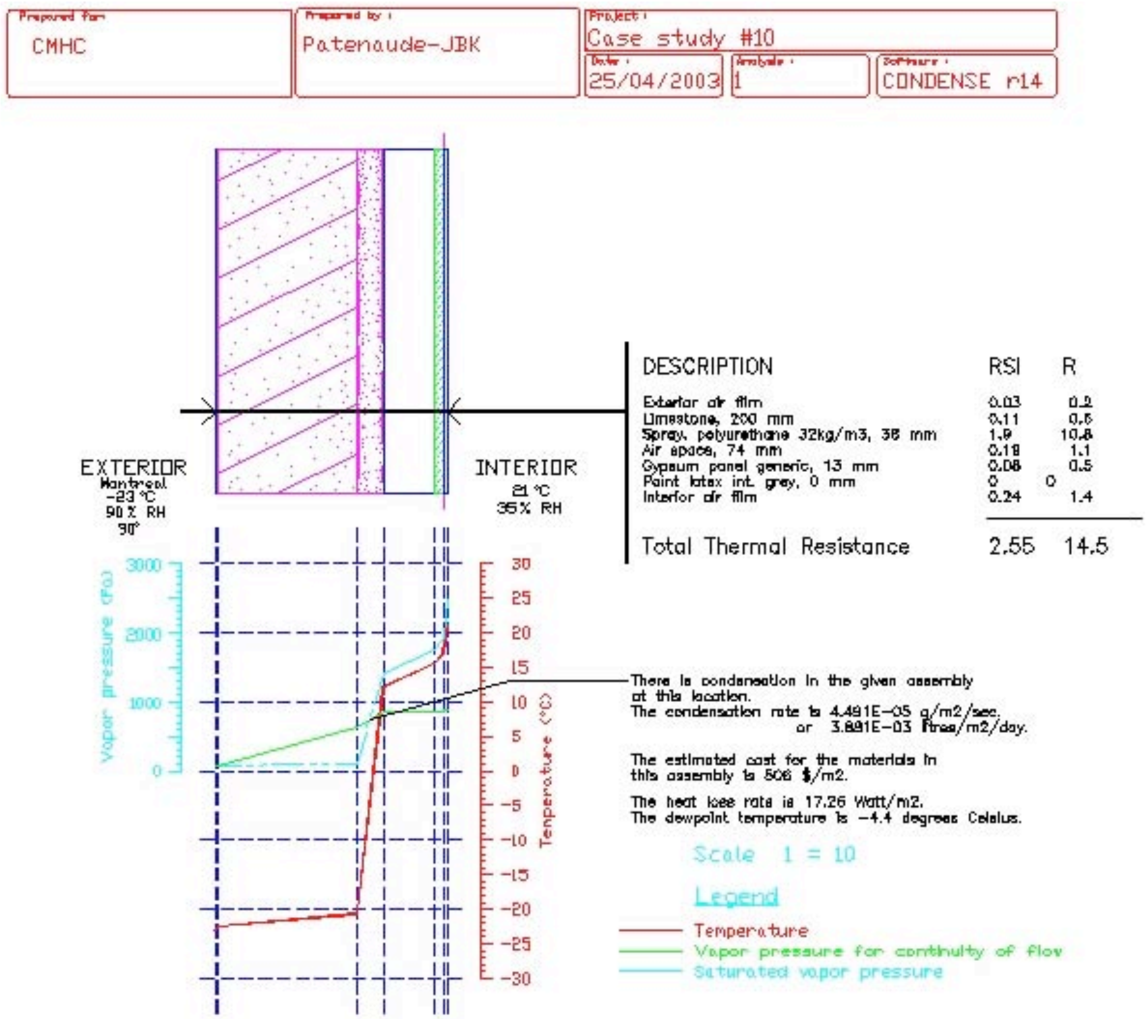
Several models of the same wall assembly were simulated presuming interior relative humidity of less than 35%. Subsequent modeling of the original wall composition (see SIM-10(25) below) showed that condensation would cease to occur presuming an interior relative humidity of 25% or less.



SIM-10(25)

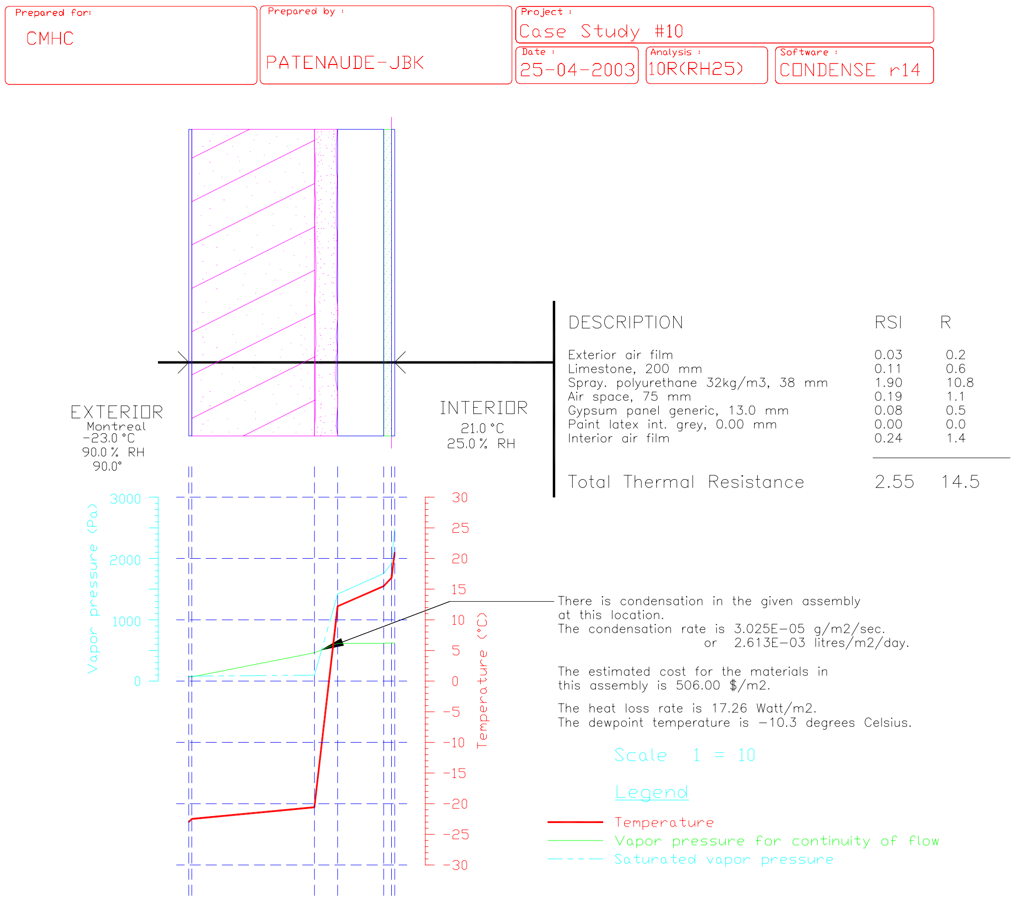
Two computer models with CONDENSE of the retrofit wall assembly of this building was also conducted with the interior relative humidity set at both 35% RH (*SIM-10R(35)*) and 25%RH (*SIM-10R(25)*). The models calculated the thermal resistance of the wall assembly to be R14.5 (RSI 2.55), while the average temperature within the stone wall is about minus -21.5 deg Celsius.

At 35% interior relative humidity, a condensation rate of 3.8 milliliters/m^2/day with a dew point temperature of minus -4.4 deg Celsius was identified within the insulation of the retrofit wall assembly.



SIM-10R(35)

At 25% interior relative humidity, a condensation rate of 2.6 milliliters/m^2/day with a dew point temperature of minus -10.3 deg Celsius was identified within the insulation of the retrofit wall assembly.



SIM-10R(25)

The THERM simulation of the retrofit assembly below (see Figure T-10) graphically illustrates the temperature of the exterior masonry to range between minus -20 deg Celsius and minus -23 deg Celsius.

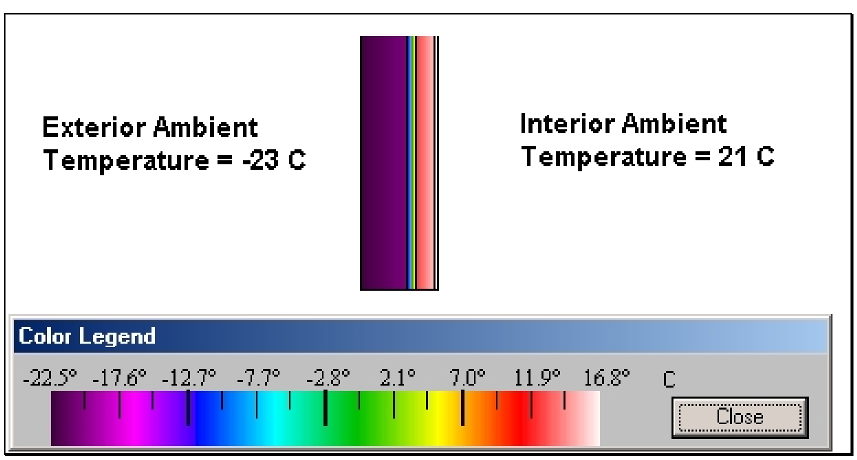


FIGURE T-10

In comparing the results of the computer modeling of both the original and the retrofit wall assemblies, it would appear to suggest that increasing the thermal resistance along the inside face of the existing masonry wall promoted conditions favorable to increasing the rate of condensation in the wall assembly under identical ambient conditions (temperature and relative humidity).

However, as no visible evidence of deterioration was observed along the exterior surface of the masonry wall at the time of our review, we are unable to establish a link between insulating existing solid masonry walls and potential accelerated deterioration of the masonry walls in the short term following the retrofit. Further intrusive review and study of the building walls in subsequent visits (every 4 to 5 years) would provide further data towards predicting the medium and long term performance of insulating solid masonry walls (see section 6.0 Conclusions).

6.0 CONCLUSIONS

At the time of our physical assessment, very little or no visible signs of deterioration were noted in all cases with the exterior solid masonry walls of the buildings. The results of these initial physical evaluations will act as a benchmark when future assessments of these same exterior solid masonry walls will be conducted.

The comparative results of the computer modeling of both the original and the retrofit wall assemblies of the case studies, appear to suggest that increasing the thermal resistance along the inside face of the existing masonry wall could provoke conditions favourable to increasing the rate of condensation in the wall assembly under identical ambient conditions (temperature and relative humidity) in six (6) of the nine (9) retrofit cases reviewed. Consequently, there is, theoretically, an increased possibility of masonry deterioration related to these six particular cases. Two (2) of the cases modeled showed that the insulative retrofit reduced the rate of condensation for these particular buildings. One of the cases which included a retrofit strategy equipped with a dynamic buffer zone system could not be effectively modeled due to the limitations of the modeling software.

However, in all cases, very little or no visible signs or evidence of deterioration were noted at the time of our survey with the exterior solid masonry walls of the buildings which could be directly attributable to the retrofit approach used.

The apparent discrepancy between the results of the computer modelling which showed an comparative increase in the rate of condensation in six of the case cases and the visual exterior review of the masonry walls which revealed no evidence of deterioration, could be explained by the following:

1. In all nine (9) cases where insulation had been added to the interior side of the masonry walls, basic building envelope design principles were followed, in particular through the installation of a suitable air-barrier and vapour barrier which limit the diffusion of humid air into the wall system during the heating season;

2. The differences in the rate of condensation between the original design and and the retrofit design of the six cases found to increase the rate of condensation through static modelling, were in all cases less than 5.0 millilitres/m^2/day, and may have little or no visible effect on the overall performance and durability of the wall systems.

3. The preliminary condition evaluation of the masonry walls was limited to only a visual exterior review of the the masonry wall. The less durable inner wythes and the effect on the steel or wood wall studs sensitive to moisture attack were not reviewed at the time of these preliminary evaluations, and as such, we are unable at this time to conclude what effect the retrofit approaches may have had on these elements. It is therefore possible that some deterioration not yet visible along the exterior masonry is in progress within the walls themselves.

4. In eight (8) of the ten (10) case studies, the exterior walls had been retrofitted less than four years prior to our preliminary visit. As a result, the physical evidence of deterioration of these solid masonry walls may

require more time and more intrusive examination (see item #3 above) before they could be observed and recorded.

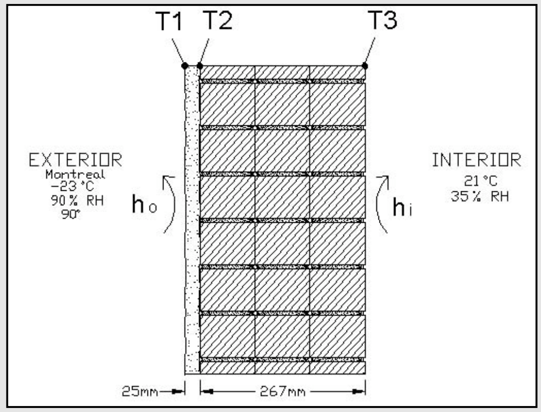
The preliminary results at this time would appear to suggest that insulating solid masonry walls in the short term do not appear to result in the deterioration of the exterior solid masonry wall when the retrofit approach involves the installation of a suitable air and vapour barrier. At this time, we have not been able to identify or obtain references to similarly retrofitted buildings with solid masonry walls which have shown clear examples of interior insulation retrofits which have caused deterioration.

An air-space in behind the exterior masonry on the cold side of the new air barrier appears to benefit the retrofit approach. In the two cases where an air space was provided on the cold side of the air barrier, static modelling showed a reduction in the comparitive rate of condensation in the retrofit wall assembly. An added benefit of this cavity or air space as in the case of common single wythe brick veneer cavity wall buildings is that it provides improved drainage in pressure equalized wall designs, reduces moisture entrapment in the wall itself, and improves the drying rate of the exterior masonry wythes through convection and air travel along the back face of the masonry.

Future visits and further study of these and other similar sites would help to provide more information regarding the effect of insulating solid masonry walls. The intent is that further study would also include intrusive reviews of the exterior wall (exploratory openings), temperature (ambient and surface) and humidity measurements, and infrared imaging of the exterior walls during the heating season in order to provide additional information regarding the overall performance evaluation of the masonry wall retrofits. The information to be gathered during these subsequent reviews and visits to these building, and the comparative analysis and performance assessment of the insulated masonry walls is intended to eventually provide practitioners with a new level of confidence when trying to determine the ideal retrofit approach for insulating buildings constructed with solid masonry walls.

APPENDIX A: CALCULATIONS

<u>Example 1</u>: Calculating surface temperatures with insulation on the exterior surface



The purpose of this example is to demonstrate the thermal effects of insulating masonry from the exterior. Typically there would be interior and exterior finishing elements in the assembly, but for the purpose of simplicity and clarity they have been omitted.

Known values:

$T_{outdoor}$ = -23 °C
T_{indoor} = 21 °C
h_o = 30 W/m^2°C
h_i = 8.3 W/m^2°C
k_{brick} = 0.84 W/m°C
$k_{polyurethane}$ = 0.024 W/m°C

The polyurethane has a thickness of 25mm and each course of brick has a thickness of 89mm.

$L_{polyurethane}$ = 0.025 m
L_{brick} = 0.267 m

The first step is to calculate the total resistance of the assembly while taking into account natural convection. The total thermal resistance of the wall, $\mathbf{R_{total}}$, is equal to the sum of the thermal resistances of each element in the assembly, namely:

$\mathbf{R_{total}} = 1/h_o + R_{polyurethane} + R_{brick} + 1/h_i$

$R_{polyurethane} = (L_{polyurethane})/(k_{polyurethane}) = (0.025)/(0.024) = 1.04$ W/m^2°C
$R_{brick} = (L_{brick})/(k_{brick}) = (0.267)/(0.84) = 0.318$ W/m^2°C

$\mathbf{R_{total}} = 1/30 + 1.04 + 0.318 + 1/8.3 =$ **1.51 W/m^2° C**

Next, the heat flow per square meter through the assembly must be calculated:

$\mathbf{Q} = \Delta T/R_{total}$ = (-23 °C – 21 °C)/(1.51 W/m^2°C) = **-29.14 W/m^2**

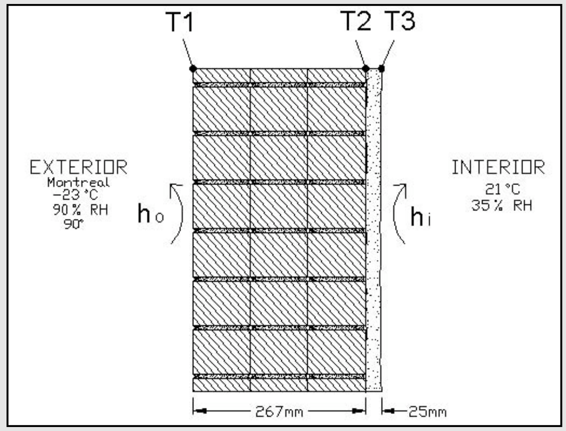
Since the heat flow through the assembly is constant, the surface temperatures T1, T2, and T3 may be calculated using the following formulae:

$Q = h_o(T_{outdoor} - T1)$
$Q = (1/R_{polyurethane})(T1 - T2)$
$Q = (1/R_{brick})(T2 - T3)$

Therefore : **T1** = $T_{outdoor} - Q/h_o$ = -23 – (-29.14)/(30) = **-22.03 °C**
T2 = T1 – Q*$R_{polyurethane}$ = -22.03 – (-29.14)*(1.04) = **8.28 °C**
T3 = T2 – Q*R_{brick} = 8.28 – (-29.14)*(0.318) = **17.55 °C**

From the results above, it is evident that the temperature in the polyurethane varies from –**22 °C** to **8 °C** and the temperature in the brick varies from **8.°C** to **17 °C**. The freezing point in the wall assembly (i.e. 0°C) is located within the polyurethane approximately 274mm from the indoor environment.

<u>Example 2</u>: Calculating surface temperatures with insulation on the interior surface



The purpose of this example is to demonstrate the effects of insulating masonry from the interior. Typically there would be interior and exterior finishing elements in the assembly, but for the purpose of simplicity and clarity they have been omitted.

Known values:

$T_{outdoor} = -23$ °C
$T_{indoor} = 21$ °C
$h_o = 30$ W/m^2°C
$h_i = 8.3$ W/m^2°C
$k_{brick} = 0.84$ W/m°C
$k_{polyurethane} = 0.024$ W/m°C

The polyurethane has a thickness of 25mm and each course of brick has a thickness of 89mm.

$L_{polyurethane} = 0.025$ m
$L_{brick} = 0.267$ m

The first step is to calculate the total resistance of the assembly while taking into account natural convection. The total thermal resistance of the wall, $\mathbf{R_{total}}$, is equal to the sum of the thermal resistances of each element in the assembly, namely:

$\mathbf{R_{total}} = 1/h_o + R_{polyurethane} + R_{brick} + 1/h_i$

$R_{polyurethane} = (L_{polyurethane})/(k_{polyurethane}) = (0.025)/(0.024) = 1.04$ W/m^2°C
$R_{brick} = (L_{brick})/(k_{brick}) = (0.267)/(0.84) = 0.318$ W/m^2°C

$\mathbf{R_{total}} = 1/30 + 1.04 + 0.318 + 1/8.3 =$ **1.51 W/m^2°C**

Next, the heat flow per square meter through the assembly must be calculated:

$\mathbf{Q} = \Delta T/R_{total} = (-23$ °C – 21 °C)/(1.51 W/m^2°C) = **-29.14 W/m^2**

Since the heat flow through the assembly is constant, the surface temperatures T1, T2, and T3 may be calculated using the following formulae.

$Q = h_o(T_{outdoor} - T1)$
$Q = (1/R_{brick})(T1 - T2)$
$Q = (1/R_{polyurethane})(T2 - T3)$

Therefore :

T1 = $T_{outdoor} - Q/h_o$ = -23 – (-29.14)/(30) = **-22.03 °C**
T2 = T1 – $Q*R_{brick}$ = -22.03 – (-29.14)*(0.318) = **-12.76 °C**
T3 = T2 – $Q*R_{polyurethane}$ = -12.76 – (-29.14)*(1.04) = **17.55 °C**

From the results above, it is evident that the temperature in the brick varies from **–22 °C** to **–12 °C** and the temperature in the polyurethane varies from -**12 °C** to **17 °C**. The freezing point in the wall assembly (i.e. 0°C) is located within the polyurethane approximately 15mm from the indoor environment.

APPENDIX B

TABLE 1 – Tabulated Summary of Buildings Reviewed

CASE STUDY	Year Built	Year of Retrofit	Location	Exterior Wall Retrofit Composition				Observations (2003)
				Cladding	Insulation	Interior Finish	Other	
1	1884	1984	Montreal	Brick (double wythe)	¾" - 1" polyurethane foam and 1¾" glass fibre batt	½" gypsum board with aluminum foil backing	No	No change in condition of masonry between visits conducted in 2000 and 2003.
2	1927	2002	Montreal	4" clay brick with 8" terra cotta block backing	1" plaster and 1" polyurethane foam	Polyethylene VB, steel furring, ½" gypsum board	No	Some minor efflorescence at windowsill and dark staining of bricks (2 facades)
3	1910	2003	Montreal	28" - 38" of solid stone	None	None	No	No masonry deficiencies
4	1918	2002	Montreal	18" solid stone	2" glass fiber	½" gypsum board with steel stud framing	DBZ system with 1" controlled and heated air space	Recently re-pointed. No apparent deficiencies.
5	1890-1905	2001	Lery	18"-24" Limestone blocks	1" polyurethane foam	Liquid VB, 2" wood stud wall, ½" gypsum board	Basement walls remain un-insulated	No apparent deficiencies.
6	1854 -1946	2003	Montreal	Variable masonry compositions (12)	1" polyurethane foam	Steel stud wall assembly with ½" gypsum board	No	Retrofit work ongoing
7	1920	2001	Montreal	4" Fieldstone, and 3 wythes of clay brick	1¼" polyurethane foam	Steel stud wall assembly, glass fibre insulation, aluminum foil backed 5/8" gypsum board	No	Good Condition, One minor crack observed.
8	1906	1996	Montreal	4" brick, 2" air space, and 8" concrete block	1½" polyurethane foam	Steel furring, Type 1 VB, ½" gypsum board	No	No apparent deficiencies.
9	1930	1999	Montreal	13" of brick (triple wythe)	1½" polyurethane foam	Steel stud wall assembly with ½" gypsum board	No	Cracks observed in brickwork at one corner of building
10	1861	2003	Montreal	Stone/Brick	1½" polyurethane foam	Steel stud wall assembly with ½" gypsum board	No	Cracks observed where stone façade meets with brick façade at corner.